

DEMAND-SIDE MANAGEMENT, EXTENDED TRANSMISSION OR STORAGE FOR SURPLUS WIND ENERGY IN THE NORTHEAST REGION?

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Abstract: Solar and wind energy are contributing ever greater proportions of utility scale generation. However due to the variable nature of wind power and solar PV, there are limits to the penetration of these technologies. This paper examines the challenges of integrating surplus solar and wind power into an electricity grid. A literature review is conducted on 3 methods used to integrate surplus wind energy, including demand-side management, extended transmission, and storage. The technical and economic advantages and drawbacks of each technology are investigated using the Brazilian Northeast region as a case study. It was found that while demand-side management is the cheapest option for integrating surplus wind power, it cannot completely resolve daily and seasonal variations in wind energy. Extended transmission lines can allow for export of surplus wind energy and import of energy during peak demand, however, very long transmission links can be costly and incur energy losses. Implementing pumped hydro storage for stockpiling excess wind energy allows for more flexibility, but the costs of constructing a new reservoir and dam makes the technology the most expensive of the 3 methods. In the future, all three methods, as well as other smart grid technologies, may be necessary to efficiently integrate renewable energy.

Keywords: Renewable energy integration, Wind power; Demand-side management, Transmission, Energy storage.

1. INTRODUCTION

The proportion of renewable energy (such as wind and solar power) is likely to play an increasing role in energy production in the coming decades. The levelised cost of electricity from wind power in Brazil is amongst the lowest across all technologies even competitive with large scale hydroelectricity (DE JONG, 2017 and CCEE, 2014). However, as solar and wind power technologies are both variable technologies (that is, the amount of energy production cannot be easily regulated to match demand) the main difficulty is not with the cost or the amount of wind and solar resources available, but rather the efficient integration of these power sources into the electricity grid. The solution to integrate the intermittent generation from these power sources is likely to involve the development of various techniques including smart grids, forecasting, controlling hydroelectric and gas plants on a sub-hourly bases to enable gap filling, interstate balancing via extended transmission lines, demand-side management and energy storage systems. For example, gap filling from dispatchable backup generators is required when output from variable renewable generation is low and demand is high.

2. LITERATURE REVIEW

Demand-side management can be implemented to utilise surplus wind energy during low demand periods, as well as reduce demand during peak demand periods (LUND et al., 2015). For example, Batas Bjelić et al. (2013) found that load flexibility via demand-side response, using controllable electric hot-water systems, could lower excess electricity production. There is huge potential for this technology to replace inefficient electric hot-water showerheads which consume 24% of residential electricity across Brazil specifically during peak demand periods (ELETROBRAS, 2005). Figure 1 shows the residential consumption of different appliances in Brazil. Furthermore, a time of day based tariff,

could encourage consumers to shift electricity consumption from peak demand hours to periods when surplus wind energy is likely to occur (DE JONG. 2017).

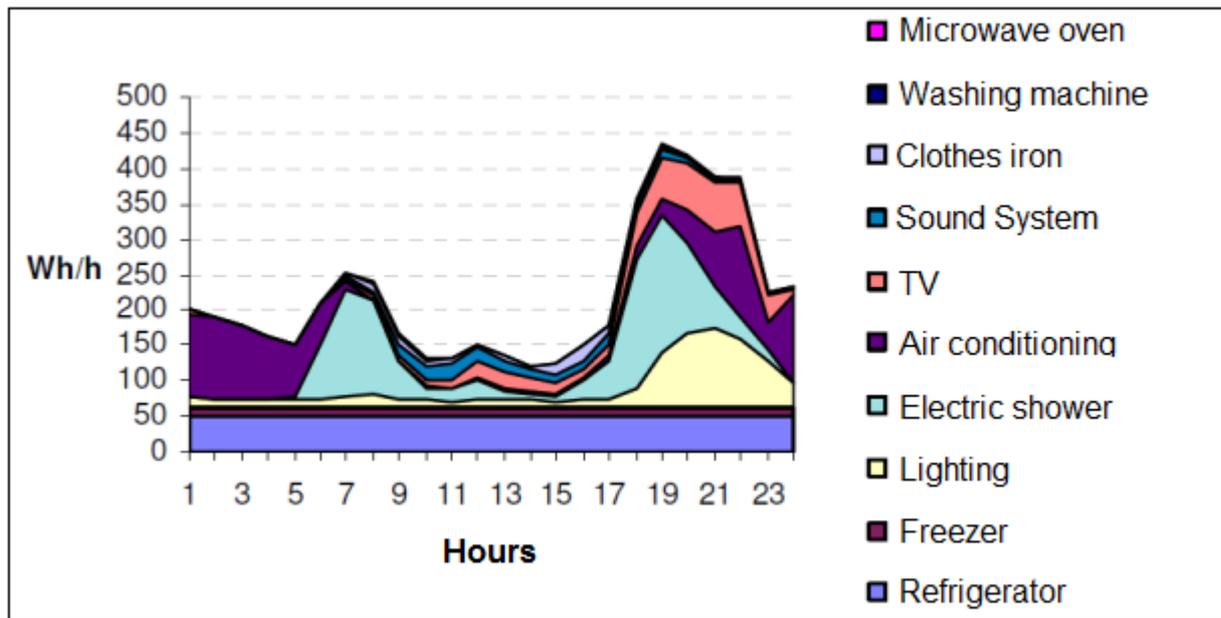


Figure 1: Daily residential load curve in Brazil. Source: Eletrobras (2005).

Alternatively, *extra-long transmission systems* could be built to interconnect widely dispersed variable generation with distant load centres and better utilise surplus wind energy. Delucchi and Jacobson (2011) make various cost estimates of extra-long transmission systems or “super-grids” to interconnect widely dispersed generation plants with load centres. The authors reviewed several North American and European studies on the cost of long transmission systems. They concluded that HVDC transmission systems (including substations, power conditioners, DC inverters and the transmission line itself) of 500-800kV with capacity of 3000MW or more, cost in the range of \$200/MW·km to \$500/MW·km, and incur power losses of 4.1% at 600kV and 2.8% at 800kV per 1000km. However, interconnecting transmission lines are also limited by the flexibility of neighbouring power systems.

Another solution is to store the excess supply of wind energy with the aid of *pumped hydro storage* (PHS). Figure 2 shows an example of a PHS system. For grid scale energy storage, pumped hydro storage (PHS) is by far the dominant technology, though other technologies such as batteries and compressed air storage are becoming competitive. PHS has an overall system efficiency of 80–90%, while the global installed capacity of the technology is estimated to be more than 150GW (REN21, 2017 and IRENA, 2015) and capacity is projected to grow to 325GW by 2030 (IRENA, 2015). China and Japan already have 21.5GW and 26GW of installed pumped storage, respectively. Other countries, such as Spain, Indonesia, Australia and Iran also use PHS technology.



Figure 2: Pumped hydro storage installation.

Hearps et al (2014) investigated and analysed the economics of installing new seawater pump hydro energy storage facilities (see figure 3) at specific coastal locations in Victoria and South Australia. Depending on the electricity price data modelled, the payback period for a PHS facility ranged from 8 to 16 years for 5 of the locations studied. Based on that study ARENA (2017) conducted a technical and economic feasibility assessment of a proposed seawater PHS system to be installed near Port Augusta at the tip of the Spencer Gulf in South Australia.

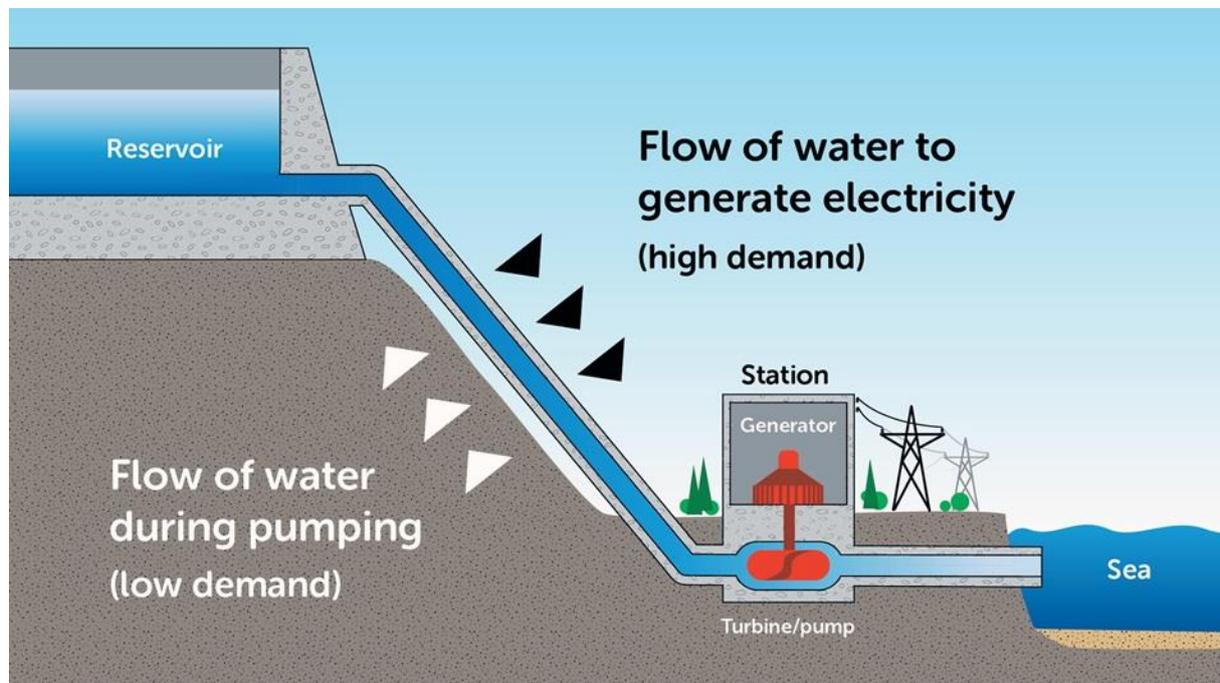


Figure 3: Schematic of seawater pumped hydro storage system.

There have been studies in Denmark, Germany, Norway and Greece on combining PHS with wind power to provide ancillary services, regulation and spinning reserve (ENDEGNANEW et al 2013 and RAHIMI et al, 2013). Specifically, PHS can increase the system load and consume surplus wind energy during low demand periods by pumping water into upper reservoirs. Therefore, wind farms are able to avoid curtailment and increase penetration, profit and operational capacity factors. During periods of peak load, when electricity prices are generally high, stored water in upper reservoirs can be used to generate electricity which is an added value for PHS operators (RAHIMI et al., 2013).

Given the existing quantity hydro-electric infrastructure already existing in Brazil this type of energy storage could be a cost effective way to utilise surplus wind and solar power provided existing dams could be retrofitted. Hunt et al. (2016) proposed a new seasonal PHS plant to be built in Muquém close to the São Francisco River which could potentially reduce evaporation from the Sobradinho reservoir and store surplus energy from the various wind farms and solar plants in the surrounding area. Further research in this area needs to be undertaken in order to fully assess the feasibility and weigh the benefits of installing a new pump hydro facility of this type in the NE region or alternatively retro-fitting suitable existing hydroelectric dams.

2.1. Review of other storage systems for variable renewable energy

There have been several studies that examine the technical issues and economics of a wide range of *energy storage systems* for variable renewable generation technologies. Sundararagavan et al (2012) and Díaz-González et al (2012) review several energy storage technologies in terms of their main characteristics, operating principles, efficiency, capital cost per MWh and describe their various applications to enable smooth integration of wind power into an electrical network. From the literature review it can be observed that capital cost estimates of energy storage systems often divided into the storage component cost and the power conversion & control system cost which can be expressed as a capital cost per MWh of installed storage capacity and per MW of installed output capacity respectively.

Hybrid power systems store energy in order to increase flexibility and reliability of an energy supply due to the uncertainty and intermittent nature of renewable sources such as wind, solar (and wave power). Various types of energy storage devices exist including batteries, hydrogen fuel cells, supercapacitors, flywheels, compressed air and pumped water storage, etc (IEA, 2014). Sundararagavan et al (2012) analysed eleven storage technologies, including lead-acid, sodium-sulphur, nickel-cadmium, and lithium-ion batteries, superconducting magnetic energy storage (SMES), electrochemical capacitors, flywheels, flow batteries, pumped hydro storage (PHS) and compressed air energy storage (CAES) systems. Figure 4 shows a schematic of CAES. The cost of these technologies is compared by considering a hypothetical storage system able to deliver power at different capacities for different durations. The study explores the 3

principal applications of energy storage including load shifting, which uses off-peak storage for peak period dispatch at the system level, frequency support at the Transmission & Distribution level, which deliver power for short durations (up to 15 minutes) and power quality at the distribution level which allow for smoothing of voltage fluctuations for durations of up to 30 seconds. It was found that CAES had the lowest cost for load-shifting followed by PHS. CAES was also the least expensive technology for frequency support closely followed by flywheels. SMES closely followed by flywheels was the least expensive technology for power quality.

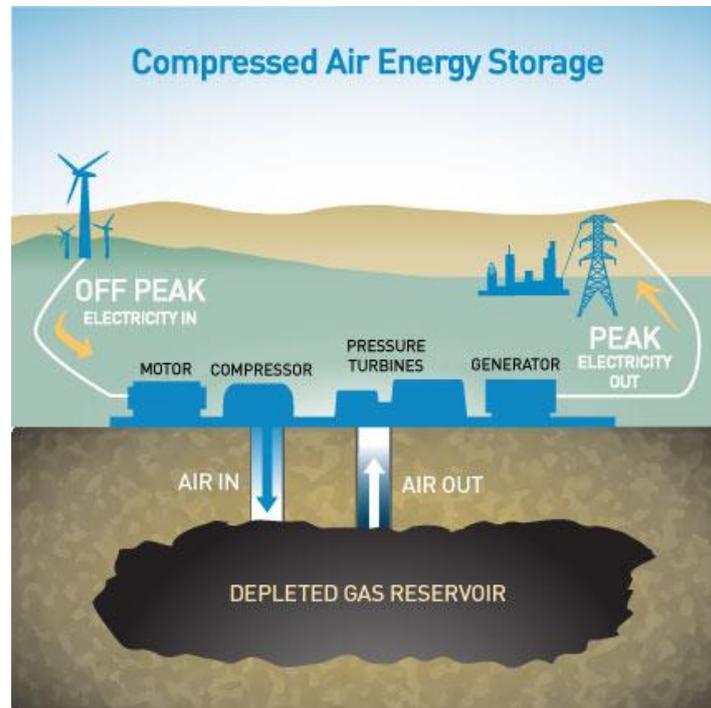


Figure 4: Schematic of a compressed air energy storage system.
Source: DOE Global Energy Storage Database (2018).

Augustine et al (2012) conducted a modelling analysis of biomass, geothermal, hydropower, solar PV, CST, wind-powered systems and their storage technologies. Estimates of resource availability, cost, output characteristics and grid service possibilities were made for each technology.

Succar et al (2006) show that wind power combined with compressed air energy storage (CAES) will become cost competitive with integrated gasification combined cycle coal with CCS when the carbon price reaches \$100/tonne of carbon (this is equivalent to \$27/tonne of CO_{2eq}). The Australian Government Treasury expects the carbon price to rise above \$75 per tonne of CO_{2eq} by 2030.

Hessami et al (2011) conducted a theoretical analysis of the economic advantages of using large-scale energy storage to complement the 190MW Portland Wind Farm located in Victoria, Australia which is connected to a base-load dominated electricity grid. Three energy storage systems were simulated: Pumped Seawater Hydro Storage (PSHS), Compressed Air Energy Storage (CAES), and Thermal Energy Storage (TES). It is found that CAES was the most profitable storage medium generating a rate of return (ROR) of 15.4%. The ROR for PSHS was 9.6% and TES was the least competitive technology with a ROR of 8.0%.

From this data the total storage system cost per MWh can be calculated and discounted over the lifetime of the system. The resulting levelised cost of energy storage can be used to compare different ways of implementing and storing renewable energy. While battery technology was found to be relatively expensive compared to other technologies, recent growth in electric vehicle battery storage production has boosted the development of advanced battery storage technologies and costs are expected to decline rapidly (IRENA, 2015 and IEA, 2014). Furthermore, the costs of rooftop solar PV combined with advanced battery storage systems will also decline and this distributed storage, if regulated properly could provide ancillary services and load shifting to support the grid (IRENA, 2015).

3. METHODOLOGY AND JUSTIFICATION

Comparing different technologies or methods to deal with surplus renewable energy quantitatively is a very complicated task because there are several ways that each technology or method could be implemented. For example demand-side management can be achieved via energy efficiency, price signals, dynamic demand or with certain appliances remotely controlled by the utility company, to name a few. Additionally, technical aspects related to transmission and energy storage systems include capacity, flexibility and energy losses amongst several others.

Therefore, this study examines each of the 3 methods from a conceptual viewpoint, applied to a real-world power system, the Brazil NE subsystem.

One of the characteristics of the NE subsystem is that by 2020 it will have a high penetration of variable renewable generation resulting in surplus generation. Specifically, the NE region is used as a case study, because by 2020, wind and solar energy will generate approximately 60% and 4%, respectively of the NE region’s electricity load, however, it is estimated there will be more than 5% surplus generation from these technologies (DE JONG, 2017). Diurnal wind power from wind farms located inland in the NE region is significantly higher at night and therefore, by 2020, most surplus wind energy in the NE will be generated during low demand periods between midnight and 08:00h (DE JONG et al., 2017a).

Furthermore, as a result of the prolonged drought in the NE region which has severely reduced the amount of stored energy in the São Francisco’s hydroelectric reservoirs, the flexibility of the NE region’s hydroelectric plants is no longer sufficient to provide all the ancillary services required to integrate variable generation from wind and solar power plants. Currently, much of the lost hydroelectric availability has been replaced by fossil fuel electricity generation, but this is expensive and unsustainable.

Therefore, this study compares 3 methods, including extended transmission, demand-side management and energy storage, which could be implemented to smooth out highs and lows of wind and solar power in the NE subsystem. The practicality of each of the 3 methods is analysed in terms of their technical and economic advantages and disadvantages.

4. RESULTS

4.1. Demand side management

The implementation of demand-side-management and energy efficiency measures (for example, by utilising variable speed drives in industry and solar hot-water systems) and could reduce peak demand and thus reduce the need for expensive peak-load following ancillary services. Electric hot-water showerheads, widely used in Brazil, could be mandatorily phased out and replaced with controllable efficient heat pump or electric resistance hot-water storage systems that can shift consumption from peak periods to low demand periods. Additionally, where installations are feasible, solar hot-water systems could be encouraged via government subsidies.

Furthermore, demand-side-management could be implemented that would enable surplus renewable energy from wind and solar sources to be more easily absorb into the NE subsystem. For example, new regulations could be introduced offering reduced tariffs during hours when surplus wind energy is likely to occur, which is typically in winter and spring between midnight and 08:00h. In 2018 a time of day based tariff called the “*tarifa branca / white tariff*” will be introduced in Brazil which is designed to encourage consumers to reduce electricity consumption during peak demand periods (between 18:00h and 22:00h). In the states of Bahia and Piauí, as well as in other states in the NE, a similar type of tariff could be implemented that offers discounted electricity between the hours of midnight and 08:00h. In Bahia the total installed capacity of wind power will grow to almost 5485MW by 2020 and wind power will have a gross penetration of approximately 69.5% in relation to the state’s average electricity demand (DE JONG, 2017). As can be observed in figure 5, most surplus wind power generation would occur between midnight and 8:00h, and the average maximum surplus energy in the month of August would be approximately 900MWavg.

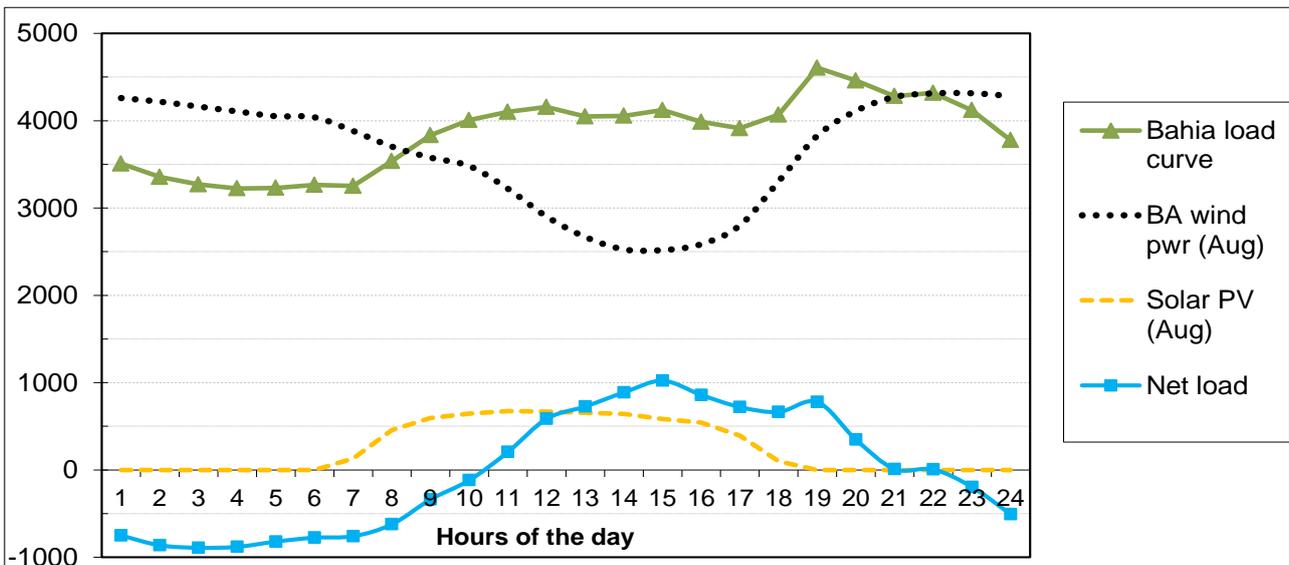


Figure 5: Bahia load curve, average solar and wind power generation and the average net load for the month of August. Note, when the net load is negative, this is an indication of surplus generation in the state. Source: de Jong et al. (2017b).

Besides reducing the need for lengthy interregional transmission lines, another advantage of fostering the consumption of surplus energy within the NE region is that this will contribute to the overall human development of the region. Currently, average consumption of electricity per inhabitant in the NE region is approximately half that of the Southeast region (MARIZ & ATALLA, 2017).

4.2. Interconnecting transmission systems

While, surplus wind and solar energy could be reduced by implementing demand side management, the technology cannot reliably deal with unexpected trough in wind and solar generation. Another solution is to reinforce interconnecting transmission lines to neighbouring regions, which would allow for power importation when required and also enable the exportation of surplus wind and solar energy during high solar and wind generation periods.

The state of Bahia, in particular, has an opportunity to export surplus wind and solar energy to load centres in the Southeast/Central-West region, such as Belo Horizonte, Brasília, Goiânia and Vitória. While there are a number of planned HVAC transmission lines that will link wind farms in Bahia to the Southeast/Central-West subsystem, it is recommended that research be done on the viability of a HVDC transmission system stretching along the wind corridor from the western edge of Piauí through the interior of Bahia and Minas Gerais to a major substation near the border with the state of São Paulo (for example Estreito). As well as increasing the efficiency of wind energy transmission and distribution from existing and planned wind farms, this would allow for the exploitation of massive amounts of untapped wind (and solar) energy potential along this wind corridor.

4.3. Pumped hydro for excess wind energy

A third solution is to store the excess supply of wind energy with the aid of pumped hydro storage (PHS). Traditionally, pumped storage has been used to reduce fuel consumption of base-load thermal power generation by supplying peak loads during high demand periods and pumping water back up to upper reservoirs during low load periods. However the application of PHS technology combined with wind farms is now becoming more common.

Endegnanew et al (2013) investigated the effects of combining offshore wind farms in the North Sea with pumped hydro storage in Norway. Two cases of power flow contingencies between Norway's pumped hydro plant and Continental Europe were simulated. In both cases Danish wind farms shutdown due to a large storm causing a reduction in generation of 2000MW. To compensate the lost wind power production Ramp Following Controllers change the power flows on the HVDC links and Load Following Controllers increase power production of other generators. In Case 1, the pumped hydro plant gradually shuts down pumping over a period of 15 minutes and in case 2 it stops pumping more rapidly and after 2 minutes begins generating power. As a result of the change in power flow in the HVDC links, the Nordic power system's frequency quality is affected. The frequency deviation is greater in case 1 than in case 2, nevertheless, in both cases the frequency remains well within the allowed operational limits of ± 1 Hz.

Given the large quantity of conventional hydroelectric storage in Brazil, wind power (and biomass generation) are used to save water in these large hydroelectric reservoirs and thereby improve energy security (IRENA, 2015 and DE JONG et al, 2016). Traditionally, conventional hydroelectric storage in Brazil has been used on a seasonal basis to store enough water during the wet season, to maintain hydroelectric generation during the dry season and droughts. However, given the projected growth in wind and solar energy in the NE of Brazil, in the future PHS plants with daily storage may be a viable alternative for storing surplus wind and solar generation (DE JONG et al, 2016 and DE JONG et al, 2017a).

Presently in Brazil there are only 4 operational PHS plants which are located in the states of São Paulo and Rio de Janeiro. The 4 relatively small plants have a total pumping capacity of less than 250MW and much of this pumping capacity is used for urban water supplies, however, several locations in Brazil have been identified and proposed for the implementation of larger PHS systems including a proposal to retrofit the Pedra do Cavalo hydroelectric plant (CANALES et al, 2015).

A feasibility study should be conducted on the Luiz Gonzaga (Itaparica) hydroelectric plant to determine whether it could be adapted to also operate as a PHS plant during hours when there is surplus wind generation in the NE subsystem. However, its operation in pumping mode would be limit to a few hours a day otherwise the average flow rate of the lower São Francisco River would drop below the minimum requirement. The Apolonio Sales (Moxotó) hydroelectric plant is another existing hydroelectric dam that could also possibly be adapted to function as a PHS facility, but without reducing the minimum flow rate requirements of the São Francisco River because the Paulo Alfonso IV plant runs in parallel with it. Hunt et al (2016) proposed a new seasonal PHS plant to be built in Muquém close to the São Francisco River in the state of Bahia. The proposed new PHS reservoir could increase the seasonal energy storage capacity of the basin, reduce evaporation from the Sobradinho reservoir and store surplus energy from the various wind farms and solar plants in the surrounding area.

5. CONCLUSION

Diurnal wind power from wind farms located inland in the states of Bahia and Piauí is significantly higher at night and before dawn during low demand periods and therefore, by 2020, most surplus wind energy will be generated between midnight and 08:00h, particularly during winter and spring (DE JONG, 2017). As implementing demand-side management via time of day based tariffs is by far the cheapest of the 3 methods analysed, it is recommended that a tariff is implemented that would encourage electricity consumption between the hours of midnight and 08:00h. However, demand-side management cannot be used to supplement generation during times of very low wind power generation. Furthermore, this kind of demand-side management is limited by consumer behaviour and the day to day and seasonal variations of variable renewable generation.

Therefore, any remaining surplus energy would still need to be dealt with. It could be exported to other Brazilian regions via new and existing transmission lines provided this is more economically viable than curtailing the surplus energy. For example, the remaining surplus wind energy from Bahia and Piauí could be exported to the large Southeast/Central-West region. There are already a number of planned HVAC transmission lines that will link wind farms in Bahia and Piauí to the Southeast/Central-West subsystem. These interconnectors will also enable the Southeast/Central-West subsystem to provide ancillary services to the NE subsystem during times of low wind power generation. However, extra-long transmission lines are costly and incur energy losses.

A third solution is to store the excess supply from wind energy with the aid of pumped hydro storage (PHS). The Apolonio Sales (Moxotó) hydroelectric plant is existing hydroelectric dam that could possibly be adapted to function as a PHS facility, without reducing the minimum flow rate requirements of the São Francisco River because the Paulo Alfonso IV plant runs in parallel with it, however, more research is required. The cost of new dams for a PHS plants could be as much as building a regular hydroelectric plant, while the capacity factor of the plant re-injecting surplus energy will always be less than 50%. Therefore, if new reservoirs and dams need to be built, then a PHS plant should only be considered after demand-side management and extra-long transmission have already been implemented and only if the cost of the new PHS plant is less than the cost of curtailing surplus energy. Nevertheless, in the coming decades as solar and wind energy penetration in Brazil increases, various smart grid technologies including energy storage may need to be implemented in order to more effectively integrate renewable energy and distributed generation.

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7. RESPONSIBILITY OF AUTHORSHIP

The authors are responsible for the content of this work.