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Forecasting, integration, and storage of renewable energy generation in the Northeast of Brazil

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"When the last tree is cut, the last fish is caught, and the last river is polluted; when to breathe the air is sickening, you will realize, too late, that wealth is not in bank accounts and that you can’t eat money."

Native American saying attributed to Alanis Obomsawin.

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ABSTRACT

As a result of global climate change, during the coming decades less rainfall and higher temperatures are projected for the Brazilian Northeast (NE). Consequently these regional climatic changes could severely impact hydroelectric generation in the NE as well as influence solar and wind power potential. The ongoing drought in the Brazilian NE region has caused hydroelectric generation to decline substantially during the last 5 years and in 2016 hydroelectricity only supplied 25% of the NE's total demand. In contrast, wind power supplied 30% of demand and is expected to generate 55-60% of the NE's electricity supply by 2020. Therefore, this paper is focused on both short term forecasting and long-term projections of renewable energy generation and resource availability. It also explores the economic, environmental and technical feasibility of renewable energy integration in the NE region of Brazil. First, the long-term impacts of climate change on the NE region's hydroelectric and wind energy production are analysed. Particular attention is paid to the long-term projections of annual rainfall and streamflow in the São Francisco basin which could decline by approximately 47% and 80%, respectively, by 2050. On the other hand, wind energy potential is projected to increase substantially during the same period. This thesis also estimates the economic, social, and environmental viability of renewable and non-renewable generation technologies in Brazil. The Levelised Cost of Electricity (LCOE) including externalities is calculated for several different case study power plants, the majority of which are located in the Brazilian NE. It was found that wind power becomes the cheapest generation technology in the NE region, once all externality and transmission line costs are taken into consideration. The LCOE for the entire Northeast's generation matrix is calculated for various configurations, including scenarios in which hydroelectric generation is restricted due to drought conditions. It was concluded that a generation mix in which wind power replaces all fossil fuel generation by 2020, could feasibly reduce the overall LCOE in the region by approximately 46% and substantially decrease CO_{2eq} emissions. Two different methods are used to examine the limits of integrating high penetrations of variable renewable generation technologies into a power system with a large proportion of hydroelectric capacity. In the first method existing wind generation data from 16 wind farms is extrapolated in time and space, while the second method uses a numerical weather prediction model to simulate future wind energy generation in the NE region. Considering the minimum generation requirements of the São Francisco's hydroelectric dams, the maximum wind energy penetration in the NE region is estimated to be approximately 50% before significant amounts of energy would need to be curtailed or exported to other Brazilian regions. Finally, this thesis reviews additional literature on energy storage and the impact of large scale variable renewable energy integration on grid stability and power quality. It was found that there are several existing technologies such as power factor and voltage regulation devices that can resolve these issues.

Keywords: Renewable Energy; Wind Power; Solar Power; Hydroelectricity; Integration; Forecasting.

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RESUMO

Como consequência da mudança climática global, nas próximas décadas menos precipitação e temperaturas mais altas são projetados para Nordeste (NE) do Brasil. Consequentemente, essas mudanças climáticas regionais podem afetar severamente a geração hidrelétrica no NE, bem como influenciar o potencial de energia solar e eólica. A seca atual nessa região do Brasil fez com que a geração hidrelétrica caísse substancialmente durante os últimos 5 anos e em 2016, as usinas hidrelétricas apenas forneceram 25% da demanda total do NE. Em contraste, a energia eólica forneceu 30% da demanda e deverá gerar 55-60% do fornecimento de energia elétrica do NE até 2020. Portanto, este trabalho está focado tanto na previsão a curto quanto projeções a longo prazo da geração de energia renovável e disponibilidade de recursos. Ele também explora a viabilidade econômica, ambiental e técnica da integração de energias renováveis na região NE. Primeiramente, os impactos de longo prazo das mudanças climáticas na produção hidrelétrica e eólica da região NE são analisados. Especial atenção é dada às projeções de longo prazo de precipitação anual e fluxo na bacia do São Francisco, que podem diminuir em aproximadamente 47% e 80%, respectivamente, até 2050. Por outro lado, prevê-se que o potencial da energia eólica aumente substancialmente durante o mesmo período. Esta tese também estima a viabilidade econômica, social e ambiental das tecnologias de geração renováveis e não-renováveis no Brasil. O custo nivelado de energia elétrica (LCOE), incluindo externalidades, é calculado para diversas usinas de estudo de caso, a maioria localizada no NE. Verificou-se que, a energia eólica se torna a tecnologia de geração mais barata na região NE, uma vez que todos os custos de externalidades e de linhas de transmissão são levados em consideração. O LCOE para a matriz de geração do Nordeste é calculado para várias configurações, incluindo cenários em que a geração hidrelétrica é restrita devido às condições de seca. Concluiu-se que, uma mistura de geração em que a energia eólica substitui toda a geração de combustíveis fósseis até 2020, poderia reduzir o LCOE na região em aproximadamente 46% e diminuir substancialmente as emissões de CO2eq. Dois métodos diferentes são usados para examinar os limites da integração de altas penetrações de tecnologias de geração renovável variáveis em um sistema de energia com uma grande proporção de capacidade hidrelétrica. No primeiro método, dados de geração eólica existentes de 16 parques eólicos são extrapolados no tempo e no espaço, enquanto o segundo método utiliza um modelo de previsão numérica de tempo para simular a futura geração de energia eólica na região NE. Considerando as exigências mínimas de geração das hidrelétricas do São Francisco, estima-se que a penetração máxima de energia eólica na região NE seja de aproximadamente 50% antes que quantidades significativas de energia precisem ser desperdiçadas ou exportadas para outras regiões brasileiras. Finalmente, esta tese examina literatura adicional sobre armazenamento de energia e o impacto da integração de energia renovável variável em larga escala na estabilidade da rede elétrica e na qualidade da energia. Verificou-se que existem várias tecnologias existentes, como dispositivos de regulação de fator de potência e tensão que podem resolver estes problemas.

Palavras-chave: Energia Renovável; Energia Eólica; Energia Solar; Hidroeletricidade; Integração; Previsão.

LIST OF ABREVIATIONS, ACRONYMS AND SYMBOLS

°C	Degree Celsius
AEMO	Australian Energy Market Operator
AMSL	Above mean sea level
ANA	Agência Nacional de Águas/National Water Agency
ANEEL	Agência Nacional da Energia Elétrica/Brazilian Electricity Regulatory Agency
ARW	Advanced Research WRF
ATSE	Australian Academy of Technological Sciences and Engineering
Avg	Average
BEN	Bioenergia
BIG	Banco de Informações de Geração/Generation Information Bank
BRAMS	Brazilian Regional Atmospheric Modelling System
CAES	Compressed Air Energy Storage
CCEE	Câmara de Comercialização de Energia Elétrica
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Collection and Sequestration
CERs	Certified Emission Reductions credits
CMIP5	Coupled Model Inter-comparison Project Phase 5
CO_2	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equivalent
COELBA	Companhia Elétrica da Bahia/Electric Company of Bahia
CPTEC	Centro de Previsão de Tempo e Estudos Climáticos
CSP	Concentrated Solar Power
CST	Concentrated Solar Thermal
DFIGs	Doubly fed induction generators
ECMWF	European Centre for Medium- Range Weather Forecasts
EPE	Empresa Pesquisa Energética/Energy Research Company
EUAs	European Union carbon Allowances
ExternE	Externalities of Energy
FCAS	Frequency Control Ancillary Services
FSWTs	Fixed-speed wind turbines
GDP	Gross Domestic Product
GENESYS	Genetic Optimisation of a European Energy Supply System

GHG	Greenhouse Gases
HOMER	Hybrid Optimization Model for Electric Renewables
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
INPE	Instituto Nacional de Pesquisas Espaciais/National Institute for Space Research
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt hours
LCA	Life Cycle Analysis
LCOE	Levelised Cost of Electricity
LVRT	Low-voltage-ride-through
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
mm	Millimetres
MME	Ministério de Minas e Energia/Ministry of Mining and Energy (Brazil)
MUREIL	Melbourne University Renewable Energy Integration Laboratory
MW	Megawatts
MW_{avg}	Megawatts average / arithmetic mean
MWe	Megawatts (electrical)
MWh	Megawatt hours
NCAR	US National Centre for Atmospheric Research
NCEP	National Centres for Environmental Prediction
NCL	NCAR Command Language
NE	Northeast
NEA	Nuclear Energy Agency
NEMO	National Electricity Market Optimiser
NetCDF	Network Common Data Form
No.	Number
NO_x	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
O & M	Operations and Maintenance
ONS	Operador Nacional do Sistema Elétrico/Electrical System National Operator
P-E	Precipitation-Evaporation
PHS	Pumped hydro storage
PLEXOS	PLEXOS Integrated Energy Model
PSHS	Pumped Seawater Hydro Storage

PV	Photovoltaic
PWR	Pressurised Water Reactor
RCP	Representative Concentration Pathway
ROR	Rate of return
SAM	System Advisor Model
SEPLANDE	Secretaria de Estado do Planejamento e do Desenvolvimento Econômico
SMES	Superconducting magnetic energy storage
SO_2	Sulphate Dioxide
SRES	Special Report on Emissions Scenarios
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation
STATCOM	Static synchronous compensator
SVC	Static VAR compensator
SWERA	Solar and Wind Resource Assessment
TES	Thermal Energy Storage
TWD	tail water depression
UNFCCC	United Nations Framework Convention on Climate Change
VAR	Volt-ampere reactive (reactive power)
WRF	Weather Research and Forecasting

Table of Contents

INTRODUCTION

The challenges human civilisation will face during the 21st century will be complex and unprecedented. Global demand for energy and agriculture will increase substantially as 3rd world and developing countries advance their economies, and also because of global population growth, which will see an estimated 10 billion inhabitants by 2050. While some ancient human civilisations rose only to be conquered, other ancient civilisations have risen and finally fallen due to lack of resources, famine, civil war and greed.

According to Rockström et al (2013) and Steffen et al (2015) modern civilisation has already overstepped at least 4 planetary boundaries for a safe living environment including climate change, biodiversity/genetic diversity losses, land-system change and the nitrogen and phosphorous cycles. If modern civilisation is to stop history repeating itself, it will require a united effort from all sectors of the global community, including government, business, academia, science, agriculture, consumers and all other stakeholders. Both government and corporations will need to collaborate together in scientific research and technological development to achieve sustainable energy generation and agricultural production.

The Paris Agreement to limit the global temperature rise well below 2 degrees Celsius above pre-industrial levels officially entered into force on the 4th of November 2016 and to date, 141 countries have ratified the agreement. However, there are still large discrepancies between science-based targets to achieve the Paris Agreement goal and actual national commitments (ROCKSTRÖM et al, 2017). It has been estimated that the Intended Nationally Determined Contributions from each nation will, at best, limit the global temperature rise to approximately 2.7–3 degrees Celsius by 2100 (UNFCCC, 2015). Moreover, the recent withdrawal of the USA from the Paris Agreement will make it even more difficult to achieve the goals of the Agreement. According to Rockström et al (2017) keeping the global temperature rise below 2 degrees Celsius would require halving global greenhouse gas (GHG) emissions every decade from 2020 until 2050, as well as ramping up CO_2 removal technologies such as afforestation and carbon capture and sequestration from bioenergy.

However, halving emissions every 10 years will be particularly challenging considering that global (gross domestic product) GDP typically doubles every 25-30 years (WORLD BANK, 2017). Energy efficiency technologies will have a role to play and can be cost effective, however, there are physical limits set by thermodynamics to efficiency gains that can be achieved. Thus, each incremental increase in efficiency after initial gains generally becomes more complex and costly to implement. As a result, efficiency technologies will not enable an absolute decoupling between growth in GDP and resource consumption (JACKSON, 2009). Therefore, reducing net emissions to virtually zero by 2050 may actually require a form of “de-growth” particularly when it comes to limiting global energy and resource consumption. “De-growth” is an emerging theory where human prosperity is maintained or improved in a sustainable way by limiting or reducing resource and energy throughput to a point where a sustainable steady state economy can be attained (JACKSON, 2009). Yet, to date, no country in the world has achieved a true environmentally sustainable steady state economy (O'NEILL, 2015).

One of the biggest challenges human society faces is to generate energy without impacting on the natural environment. Traditionally, fossil fuels have been used for the majority of energy generation. However, with diminishing reserves of these non-renewable resources and ever increasing energy demands from developing countries striving for better living standards, the impacts on the environment and specifically on the earth’s climate cannot be ignored. Renewable energy technologies have existed for several years now and have the potential to substantially reduce global GHG emissions, but there are still questions over their cost, reliability and security. Moreover, the incumbent fossil fuel producers are not very willing to leave billions of dollars of mineral “assets” in the ground. Presently, 15% of global freshwater is used for fossil fuel extraction, processing and power generation, while water requirements for renewable energy technologies, such as wind energy and solar photovoltaics (PV) are negligible (IRENA, 2015). The concept of the water, energy and food nexus, in the context of climate change, is becoming an important method for assessing sustainable development goals (DODDS & BARTRAM, 2016 and GIUPPONI & GAIN, 2016).

As a result of climate change, the intensity, duration and spatial extent of droughts are projected to significantly increase during the 21st century in Southwest Australia, Northeast and Northwest Brazil, the USA, Spain, Portugal and the Mediterranean (JENKINS & WARREN, 2015). Water, energy and food security will be particularly vulnerable in the semi-arid Southwest of USA (BERARDY & CHESTER, 2017 and BARNETT & PIERCE, 2008). In recent years the Horn of Africa, southern Africa and semiarid regions of northern

Africa have experienced increasingly severe droughts and diminishing precipitation, which scientists attribute to climate change and El Niño Southern Oscillation (GAN et al, 2016). Another possible consequence of greenhouse warming is that extreme El Niño events could occur with increasing frequency (CAI et al, 2014). Moreover, El Niño occurrences are known to cause major droughts in Australia, Indonesia, Southeast Asia, parts of Africa and the Northeast of Brazil (TRENBERTH et al, 2014).

Climate change and land use changes are already impacting average temperatures and average annual precipitation in the Northeast (NE) region of Brazil. Furthermore, the NE is the most susceptible region in Brazil to severe drought, but also has the best solar and wind energy potential in the country (DE JONG et al, 2015). It will be shown that the water, hydroelectric and agricultural resources in the region are projected to further diminish in the coming decades, while the solar and wind energy potential is expected to increase. Therefore, the principal aim of this research is to investigate the viability of renewable energy integration in the Northeast region of Brazil in technical, economic, social, and environmental terms.

The Brazilian national electricity system is perhaps one of the largest and most complex power systems in the world given the large geographical area of Brazil. The national electricity systems consists of 4 interconnected subsystems including the large Southeast/Central-West subsystem, the Northeast subsystem, the North subsystem and the South subsystem. While the subsystems are interconnected, there are transmission and economic constraints, for example, in transmitting power from the South subsystem to the North subsystem. Given the particular hydrological constraints of the Brazilian NE region and its excellent solar and wind energy resources, this thesis primarily focusses on the NE subsystem. This approach also simplifies and limits a very complex and complicated problem into a more uniform and manageable scientific investigation.

Objectives

This thesis consists of 5 chapters and each chapter contains a separate article with its own objectives, literature review, methodology, results, conclusion and references.

The first article, entitled *"The impact of Climate Change on the Brazilian Northeast's electricity matrix"*, examines the long-term impacts of global warming on the NE region's hydroelectric and wind resources. Different IPCC projections of rainfall and streamflow in the São Francisco basin are compared to the historical rainfall and streamflow trends. The initial results of this article demonstrate a necessity for the NE region to adapt its electricity matrix in order to avoid future energy deficits. Besides highlighting the planning that will be required to mitigate the inevitable water shortages in the region, the first article is also a justification for the subsequent 4 articles in this thesis which focus on the feasibility and integration of renewable generation in the NE region.

The second article, entitled *“Economic and environmental analysis of electricity generation technologies in Brazil”*, was published in Renewable and Sustainable Energy Review in 2015. The article focusses on the economic, social, and environmental viability of renewable and non-renewable generation case studies located predominately in the NE region of Brazil. Specifically the Levelised Cost of Electricity (LCOE) is calculated for 13 different case study plants. Furthermore, for each power plant, the costs of environmental and social externalities such as greenhouse gas (GHG) emissions and air pollution are estimated in terms of health damage costs and greenhouse gas damage costs.

The third article, entitled *“Integrating large scale wind power into the electricity grid in the Northeast of Brazil”*, was published in Energy in 2016. The article examines the feasibility of integrating large scale wind power into an electricity grid (the Brazilian NE subsystem) which has a high proportion of existing hydroelectricity. The theoretical maximum feasible penetration of wind energy in various states and the entire Northeast subsystem is estimated. Additionally, the LCOE for the Northeast subsystem generation matrix is compared under various conditions, including drought scenarios and scenarios where wind power replaces all fossil fuel generators.

The fourth article, entitled *“Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid”*, published in Applied Energy 2017, is similar to the third article in that it also estimates maximum feasible penetration of wind energy in the region, however, the novelty of the fourth article is that it uses a numerical weather prediction tool to forecast wind power integration across several geographically dispersed locations of both existing and future wind farms. The third article estimated the hourly and monthly aggregate wind power production in the Brazilian NE region by 2020, based on observed wind power generation data from 16 existing wind farms located in the region. But rather than extrapolating observed wind power data, the fourth paper simulates wind power generation using the WRF (Weather Research and Forecasting) model, based on the planned installation of more than 600 wind farms across all 8 states in the NE subsystem. Furthermore, the methodology in the fourth paper also considers the minimum flow requirements of the São Francisco River in order to estimate the minimum generation level of the NE's hydroelectric plants.

The fifth article, entitled *"The impact of wind power and PV integration on the stability of the grid"*, reviews some additional literature on energy storage and the impact of large scale renewable energy integration on the stability of the grid. The article also investigates the effects of large scale PV and wind integration on the Australian national electricity market, as well as the benefits of using pumped hydro to store excess wind energy.

The conclusion and recommendations section of this thesis summarises what was achieved. An overview is given of the main proposals that could improve variable renewable energy integration in Brazil and in the NE region. Some of the findings are updated with more recent data. For example, some of the LCOE results in chapter 2, which was first published in 2015, are revised with new data and presented in appendix A. Additionally presented in appendix A, is amended data for the installed wind power capacity and electricity demand expected in the NE subsystem by 2020. In appendix B, the complementarity of wind, PV and concentrated solar thermal (CST) power in Bahia is investigated.

CHAPTER 1

The impact of Climate Change on the Brazilian Northeast's electricity matrix

The impact of Climate Change on the Brazilian Northeast's electricity matrix

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ABSTRACT

By the end of this century higher temperatures and significantly reduced rainfall are projected for the North and Northeast (NE) regions due to Global Warming. Furthermore, the reduced rainfall predicted for the North and NE regions will have a negative impact on the Electricity Matrix in these regions of Brazil. This study examines the impact of these long-term rainfall changes on the Brazilian Northeast's hydroelectricity and biomass production. Various studies that use several different IPCC models are examined in order to determine the percentage of average rainfall reduction by 2100 in comparison to baseline data from the end of the 20th century. It was found that average annual rainfall in the NE region could decrease by approximately 25-60% depending on the emissions scenario. Analysis of historical rainfall data in the São Francisco basin during the last 56 years showed a reduction of 25% from the 1961-90 long-term average. If this decline continues rainfall reduction in the basin could be even more severe than the worst IPCC model projections. Due to the elasticity factor between rainfall and streamflow and because of increased amounts of irrigation in the São Francisco basin, the reduction in the NE's average hydroelectric production by the end of the century could be double the predicted decline in rainfall. Conversely, it is estimated that by 2100, wind power potential in the Brazilian North and NE will more than triple the 2001 baseline reference. Additionally, the decline in rainfall projected for the NE and North regions due to climate change will also cause a significant increase in the regions' average solar radiation levels. Therefore both wind and solar power will need to be significantly exploited in order for the NE region to maintain its relatively low emissions factor from electricity generation.

Keywords: Climate change; Rainfall; Hydroelectricity; Renewable energy; Drought.

1. INTRODUCTION

The Northeast (NE) region of Brazil is composed of 9 states and has a population of 53.6 million people which is more than a quarter of Brazil's entire population. While Brazil overall has the world's largest water resources, Brazil's Northeast region (NE) receives only a fraction of the total annual national rainfall (DE JONG et al, 2013). The interior of the NE region is mostly semi-arid and suffers from frequent droughts, which can also affect the region's power supply. This is because the majority of the NE's electricity (typically 70%) was supplied from hydroelectric dams that are located in the NE's São Francisco basin (see figure 1) which is one of the driest regions in the country.

Figure 1: The NE region´s São Francisco basin, reservoirs and dams.

However, as a result of a drought in the region which began in 2012, in 2013, 2014, 2015 and 2016 these hydroelectric plants only contributed 42%, 39%, 31% and 25%, respectively, of the NE's total electricity demand. The effect on hydroelectricity generation is illustrated in figures 2 and 3. This shortfall was mostly substituted by fossil fuel power. Moreover, in November 2015 the water volume level in the São Francisco reservoirs fell to only 5% of the total capacity in terms of stored energy (its lowest level since all the dams were completed in 1994) and in November 2016 the volume level was only marginally better at 9% (ONS, 2017). As a consequence of the continuing drought, in late 2016, ANA (Agência Nacional de Águas) reduced the São Francisco River's lower-middle flow rate from 800m^3/s to 700m^3/s (ONS, 2016) and in May 2017 the flow rate was reduced again to 600m^3/s (CHESF, 2017). This is significantly below the minimum rate of 1,100-1,300m^3/s traditionally set by the ANA (ONS, 2012) to avoid ecological problems such as increased salinization in the lower São Francisco. As a result, the NE's hydroelectric generation for 2017 is projected to be approximately 2500MW$_{avg}$, which will be the lowest figure since all the São Francisco hydroelectric plants were completed. The drought is now in its sixth year and ANA is currently considering reducing the flow to 550m^3/s.

However, Global Warming, which will affect the long-term temperature and rainfall patterns in the NE region, may threaten hydroelectricity production to an even greater degree. Therefore the objective of this paper is to analyse existing literature on the impacts of climate change on the water and wind resources of the NE region and estimate how hydroelectricity and wind power generation will be affected. Furthermore, the relationships between historical rainfall data, natural streamflow, hydroelectric production and hydroelectric availability are also examined. Considering these relationships and other influences such as climate change, increased irrigation, evaporation and infiltration in the São Francisco basin, average streamflow and hydroelectric production for 2030, 2050 and 2100 are estimated for various rainfall reduction projections and by extrapolating the trend in historical rainfall data. Other consequences of decreased rainfall in the NE's semi-arid region are also discussed.

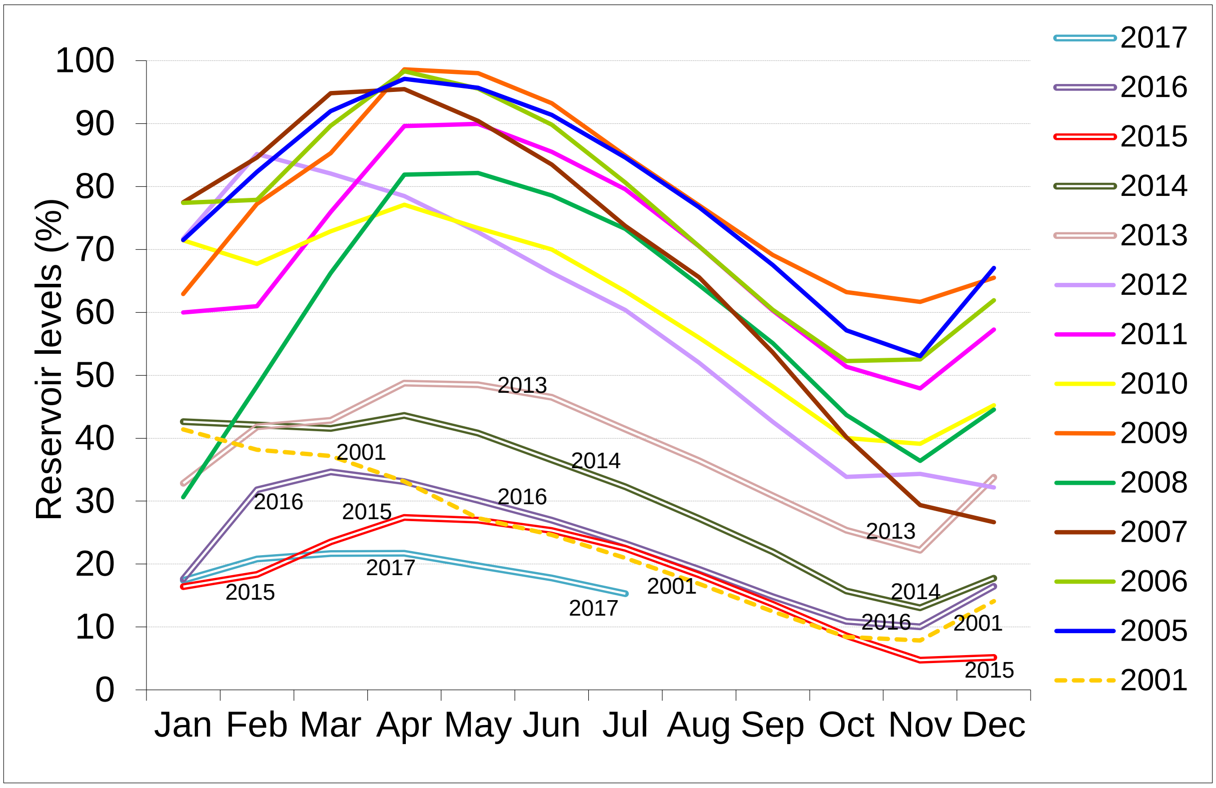


Figure 2: NE Reservoir Volume Levels (as percentage of the total capacity) 2001 and 2005-2017. Source: ONS (2017).

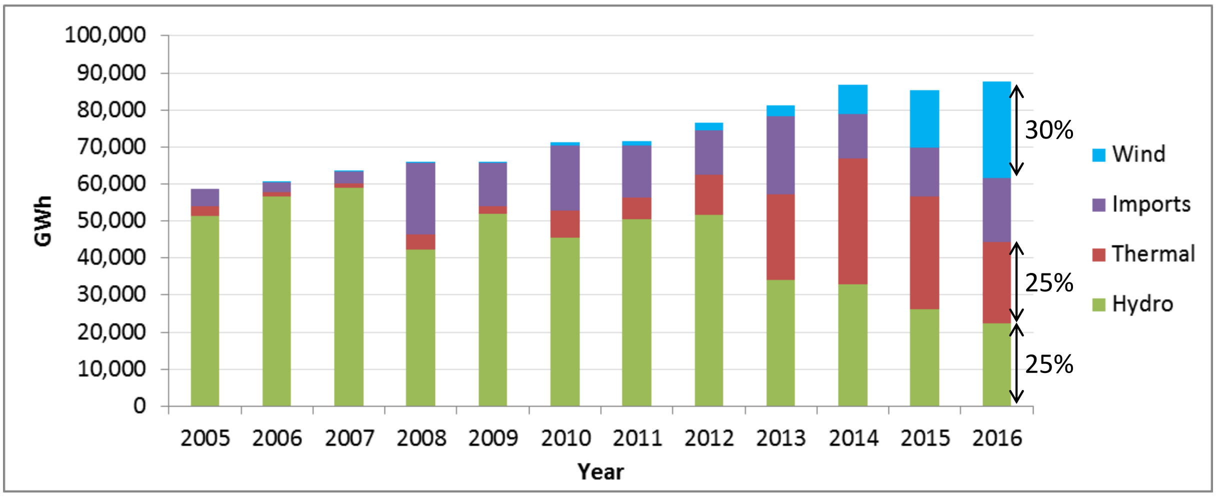


Figure 3: Sources of the Northeast's Electricity. "Thermal" electricity generation in the NE is from fossil fuels & biomass. "Imported" consists mostly of hydro from other Brazilian regions. From 2005-2007, hydro was responsible for more than 87% of the NE's electricity supply. Source: ONS (2017).

2. LITERATURE ON THE IMPACT OF CLIMATE CHANGE ON THE BRAZILIAN NORTH AND NORTHEAST

By 2070, temperatures in the interior of the NE are projected to increase approximately 4–5°C and rainfall could decline approximately 25–50% in semi-arid areas of Bahia and up to 80% in coastal areas. This will cause a reduction in flow rates of 60–90% for various rivers in the NE (TANAJURA et al 2010). According to Lucena et al (2010) the climate in Brazil's North region, which today is very humid, will become drier with less rainfall toward the end of the 21st century.

Higher temperatures and significantly reduced rainfall are predicted for the North and NE regions due to Global Warming and these climatic changes will also threaten hydroelectricity and biomass production in these regions of Brazil. Conversely, it is estimated that by 2070, wind power generation potential could more than double the 2001 reference baseline potential, and by 2100 it will more than triple the reference baseline (LUCENA et al, 2010). Similarly, a study by Pereira et al (2013) forecast more conservative increases of 15-100% in wind power density for most of the NE region by the end of the 21st century. Additionally, the decline in rainfall projected for the NE and North regions due to climate change could also cause a significant increase in the regions' average solar radiation levels. Therefore both wind and solar power will need to be significantly exploited in order for the NE region to maintain its relatively low emissions factor from electricity generation.

The Northeast region is privileged with huge solar and wind resources, nevertheless, it imports significant percentages of electricity from the North and Southeast regions (DE JONG et al, 2013). Furthermore, climate change mitigation will increase the demand for emissions free electricity generation such as the use of more hydropower (SCORAH et al, 2012). However, another effect of climate change is that the hydroelectric potential in the São Francisco basin will be reduced due to more frequent and intense climate induced droughts (DE JONG et al, 2013, LUCENA et al, 2009 and MARENGO et al, 2016).

According to Marengo (2008b) the most vulnerable areas to climate change and climatic extremes in Brazil are the Amazon and the Northeast. The IPCC AR4 models predict reductions in rainfall in the Brazilian North and Northeast and reductions in the river flows of the São Francisco, Parnaíba, Tocantins, Xingu river basins (MARENGO, 2008b). The IPCC SRES (Special Report on Emissions Scenarios) A2-high emissions scenario shows an alarming reduction in rainfall in the North and NE regions of Brazil by 2100 which can be observed in figure 4. Likewise, the temperature increase by 2100 compared to the 1990 baseline is shown in figure 5.

Low rainfall, river flows and extended drought in the Northeast region are also linked to El Niño phenomenon (MARENGO, 2008a and MARENGO 2008b) and inter-decadal variability (MARENGO, 2007). However, long-term projections indicate there will be a trend for an increase in the frequency of consecutive dry days in the eastern Amazon and in the Northeast region (MARENGO, 2008a and MARENGO 2008b). According to Marengo (2008b) and Marengo & Nobre (2007) despite the expected completion of the huge project to transpose water from the São Francisco River, more than 40 million people living in the Northeast’s semi-arid region could experience a shortage of drinking water by 2025. By the end of the century much agricultural land could be severely damaged and desertification will likely occur in parts of the Northeast’s semi-arid region which could result in food shortages and famine on a massive scale (MARENGO, 2008b and MARENGO et al, 2016) as well as negatively impacting on biomass production. Additionally, the Northeast is highly vulnerable because of its dependence on water resources for electricity generation.

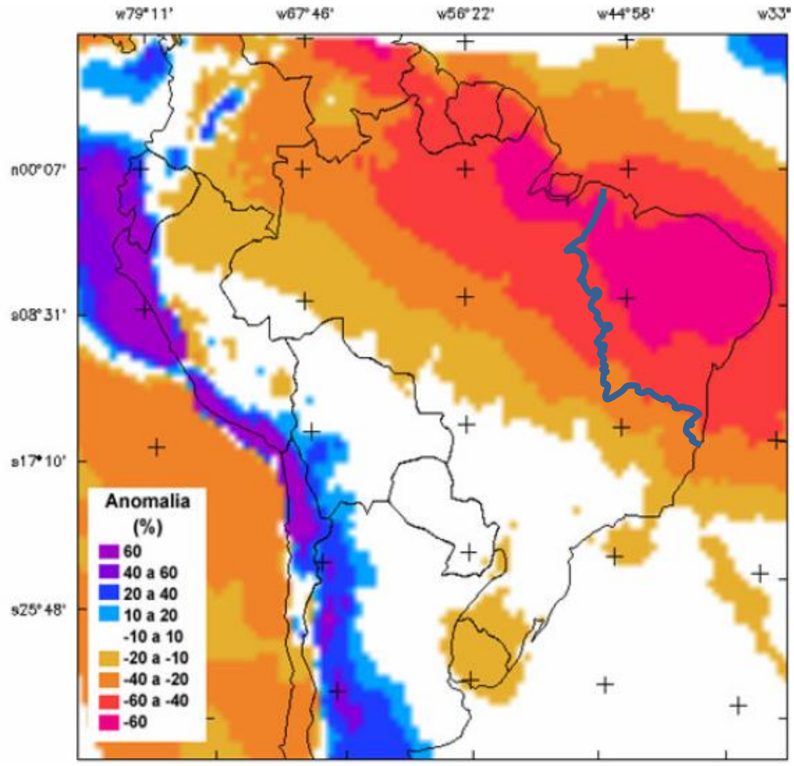


Figure 4: Projections of annual rainfall (%) anomalies for the A2 (RCP8.5) emissions scenario for 2071-2100 relative to 1961-90 using an ensemble of the 3 regional models (Eta CCS, RegCM3 and HadRM3P). Source: Marengo (2008a) and Marengo & Ambrizzi et al (2007).

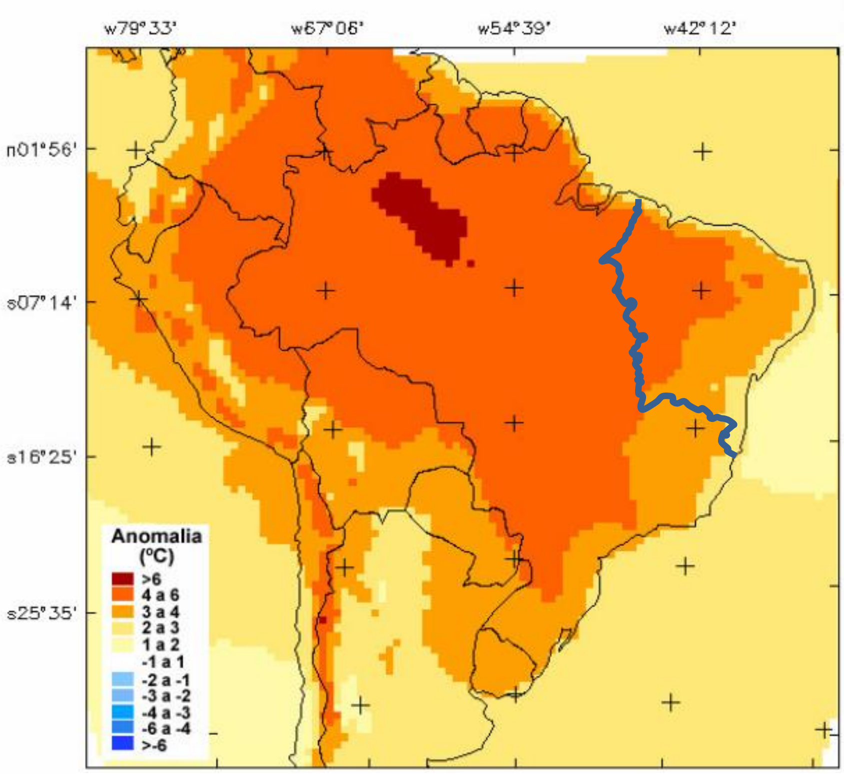
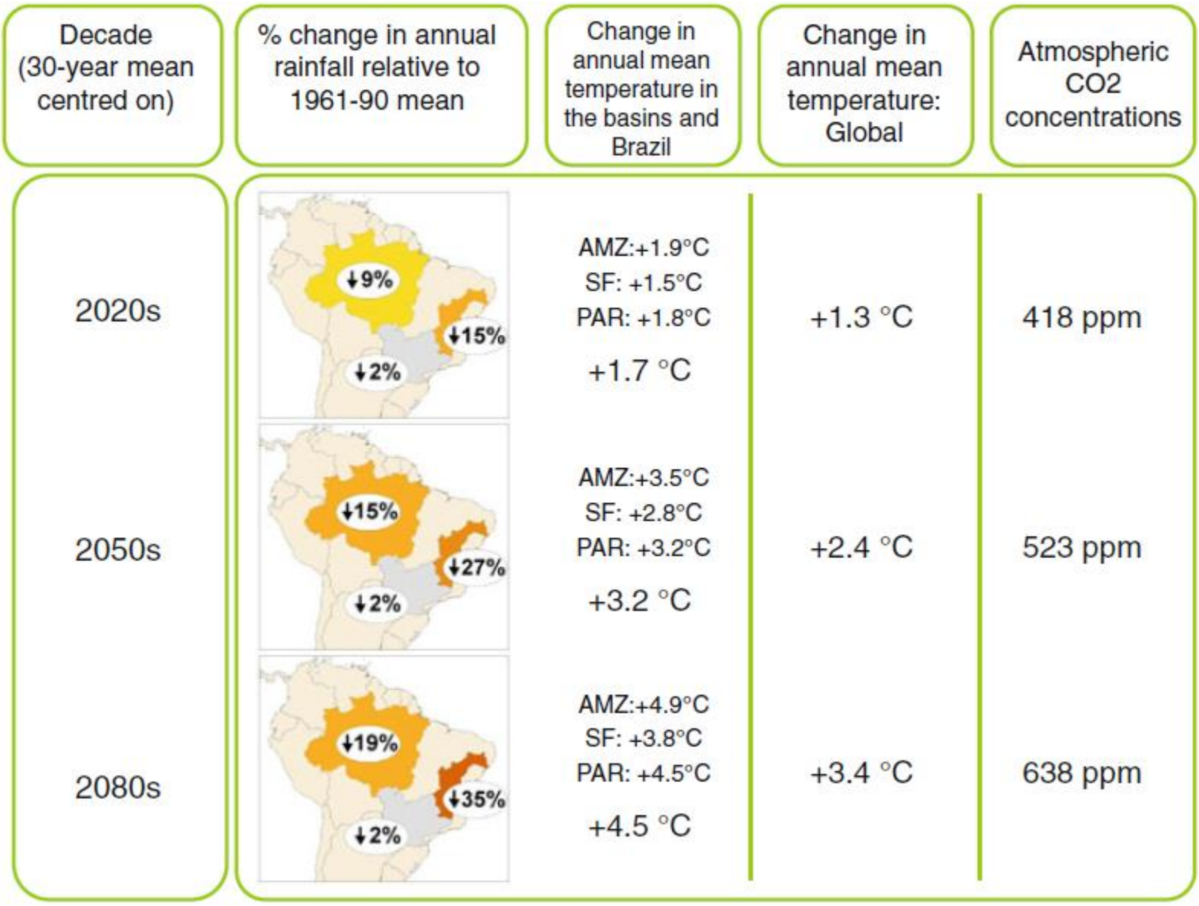


Figure 5: Projections of annual air temperature (°C) anomalies for the A2 (RCP8.5) emissions scenario for 2071-2100 relative to 1961-90 using an ensemble of the 3 regional models (Eta CCS, RegCM3 and HadRM3P). Source: Marengo (2008a) and Marengo & Ambrizzi et al (2007).

According to Marengo et al (2012) the hydroelectric potential of the São Francisco River is already over exploited with a total capacity of approximately 10,400MW (see figure 7, RHS). By 2100, rainfall is projected to decrease in the Amazon region and the São Francisco River basin of approximately -1mm/day relative to 1961–1990 baseline (MARENGO et al, 2012), considering the IPCC B2 stabilised emissions scenario (which lies between the RCP4.5 and RCP6.0 scenarios). The rainfall reductions in summer will be more pronounced reaching 2mm/day in Amazon and 3.5mm/day in the São Francisco Basin. This equates to overall annual rainfall reductions by 2100 of 19% in the Amazon, 35% in São Francisco basins and 20% across Brazil as a whole (MARENGO et al, 2012). These projections are summarised in figure 6.

Furthermore, it is projected that there will be at least a 30% decrease in the Precipitation-Evaporation (P-E) difference over the eastern Amazon basin and much of Northeast region as a result of a combination of higher temperatures and reduced rainfall (MARENGO et al, 2012). This will result in less soil moisture and lower river flows, which could lead to soil degradation, drought and desertification of semiarid land.



Decade (30-year mean centred on)	% change in annual rainfall relative to 1961-90 mean	Change in annual mean temperature in the basins and Brazil	Change in annual mean temperature: Global	Atmospheric CO2 concentrations
2020s	↓9% ↓15% ↓2%	AMZ:+1.9°C SF: +1.5°C PAR: +1.8°C +1.7 °C	+1.3 °C	418 ppm
2050s	↓15% ↓27% ↓2%	AMZ:+3.5°C SF: +2.8°C PAR: +3.2°C +3.2 °C	+2.4 °C	523 ppm
2080s	↓19% ↓35% ↓2%	AMZ:+4.9°C SF: +3.8°C PAR: +4.5°C +4.5 °C	+3.4 °C	638 ppm

Figure 6: Projected climate change over Brazil and the Amazon (AMZ), São Francisco (SF) and Paraná (PAR) River basins relative to 1961–1990. Source Marengo et al (2012).

According to Marengo & Bernasconi (2015) global projections from the HadCM3 models for the RCP4.5 scenario (similar to the B1 scenario) suggest a substantial reduction in the water balance by 2100 resulting in a P-E deficit of (3–4 mm/ day) and a rainfall reduction of about 22% across the NE region. However, compared to the majority of the NE region, a much bigger reduction in rainfall and P-E can be observed in the Upper and Middle São Francisco basin by examining the projection maps published by Marengo & Bernasconi (2015).

Using the PRECIS model, which downscales the HadCM3 global climate model, Lucena et al (2009) estimated that the average annual streamflow in São Francisco basin would drop around 23-27% by the end of the century. They also calculated a corresponding reduction of only 4.3-7.7% in average hydropower production. However, considering the projected deficit in streamflow, the corresponding loss in hydropower production from the São Francisco could be far more. This is assuming that average hydroelectricity production is roughly proportional to the annual streamflow. This is a reasonable assumption because since 2010 and also considering other years with below average rainfall, the São Francisco reservoirs did not reach 100% capacity and therefore almost no water was spilled in lieu of hydroelectric generation (ONS, 2017).[1] Furthermore, since Lucena et al published their paper in 2009, electricity demand in the NE and other regions has grown significantly, therefore even assuming future years with consecutively high rainfall, more hydroelectricity will be required to satisfy demand and as a result it is unlikely that significant quantities of water will be spilled in lieu of hydroelectric generation.

Considering the IPCC A2 high emissions scenario, the indications for 2100 are even more severe for the eastern Amazon and the Northeast region, where temperatures are projected to increase up to 8°C and rainfall is projected to drop by 40% (MARENGO, 2008a and MARENGO et al, 2009). These projections were derived by downscaling of the HadAM3P global model. Furthermore, estimates by PSR (2015) using the MIROC and HadGEM models, project 32% and 57% reductions, respectively, in the São Francisco's streamflow by 2030 (THE WORLD BANK, 2017). Similarly, Neto et al, (2016) found that the São Francisco's streamflow is projected to decline by 41% and 63% by the 2041-2070 period compared to the baseline, using downscaling of the MIROC5 and HadGEM2-ES models, respectively, considering the high emissions (RCP 8.5) scenario.

The Hadley models show very good precipitation hindcasting when compared to reanalysis data (SILLMANN et al, 2013), but it is important to also examine results from an ensemble of global or regional climate models. For example, results from the Climate Change Assessment and Impact Studies-La Plata Basin project, which included an ensemble of 10 regional climate models, also projects substantial rainfall reductions across the NE's semi-arid region as well as in the Upper and Middle São Francisco basin, while rainfall is projected to significantly increase in southern Brazil (IPCC, 2013). Nevertheless, while the majority of the IPCC global climate models also predict a drastic decrease in rainfall in the eastern Amazon and the Northeast region a few models predict an increase (MARENGO, 2008b). This demonstrates that there is a large degree of uncertainty when it comes to predicting long-term changes in rainfall patterns (MARENGO, 2007). Additionally, the forecasted increases in regional wind

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[1] Furthermore, by analysing historical data from the ONS (2017), it was observed that from 2010-2016 the São Francisco basin's average hydroelectricity production was 90% of the basin's average natural power/streamflow. Therefore, considering that the hydroelectric system has been operating with an efficiency of 90%, it is reasonable to assume that the average hydroelectricity production is proportional to the average streamflow.

power are also subject to various cumulative uncertainties related to the emission scenarios and climate models used (LUCENA et al, 2010 and PEREIRA et al, 2013).

3. METHOD

The average of rainfall reduction projections for the São Francisco basin by 2100 from Marengo et al (2012), Lucena et al (2009), Marengo, (2008a) and Marengo et al (2009) of 35% is used as a baseline case. However given the uncertainty with long-term rainfall forecasts, two alternative rainfall reduction cases of 20% and 50% will also be discussed.

An historical data set for the spatial average of accumulated monthly rainfall within the São Francisco basin area (see figure 7, LHS) was provided by CPTEC/INPE (Centro de Previsão de Tempo e Estudos Climáticos / Instituto Nacional de Pesquisas Espaciais).[2] Long-term averages for monthly rainfall consider time series data from 1961-1990 and the average rainfall for that period was 90mm per month (or 1083mm per year).

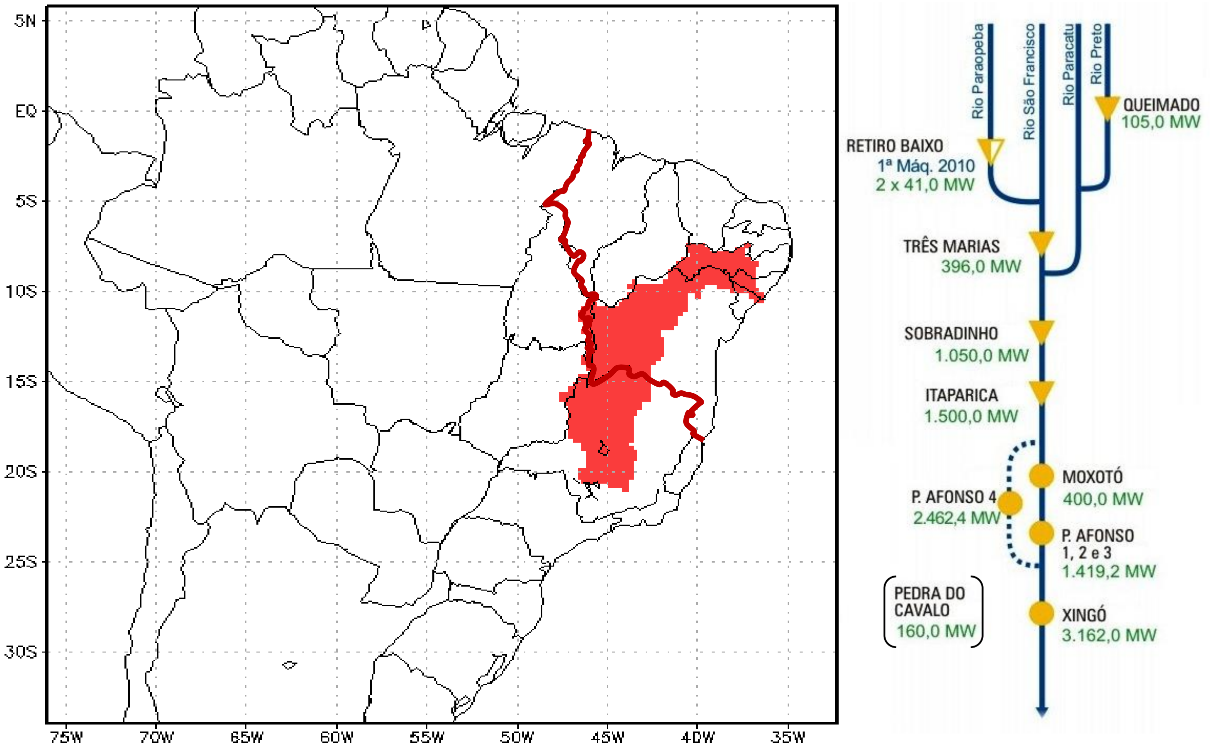

Figure 7: LHS: São Francisco basin area. RHS: Schematic of hydroelectric plants along the São Francisco River.

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[2] Historical data for the spatial average of accumulated monthly rainfall within the São Francisco basin area was calculated as follows: Daily rainfall measurements from all meteorological weather stations (classified as reliable) within and around the São Francisco basin were interpolated to a regular spatial grid. For each month with the period (1961-2017) the monthly accumulated rainfall was calculated from the daily interpolated data. Then the spatial mean of the data points, only within the area of the basin, was calculated yielding a single value for each month of the average rainfall within the São Francisco basin area.

Monthly natural streamflow and power flow data for the São Francisco River is sourced from the ONS (Operador Nacional do Sistema Elétrico). The long-term averages for natural power flow and streamflow (at Xingó) consider time series data from 1931-1990 and the averages for that period were 8500MW$_{avg}$ and 2896m^3/s, respectively. Similarly, hydroelectric generation data and hydroelectric availability data are sourced from the ONS.

In figure 8 the monthly rainfall in the São Francisco basin is shown together with the monthly natural power / streamflow data for the São Francisco River from 1961 to 2017. Both parameters are plotted as a 24 month rolling average. The decline in rainfall observed in figure 8 has not only been in the São Francisco basin, but has also been observed in the Costa das Baleias (Whale Coast) region in Bahia on the border with Espírito Santos and Minas Gerais (GENZ & TANAJURA, 2012).

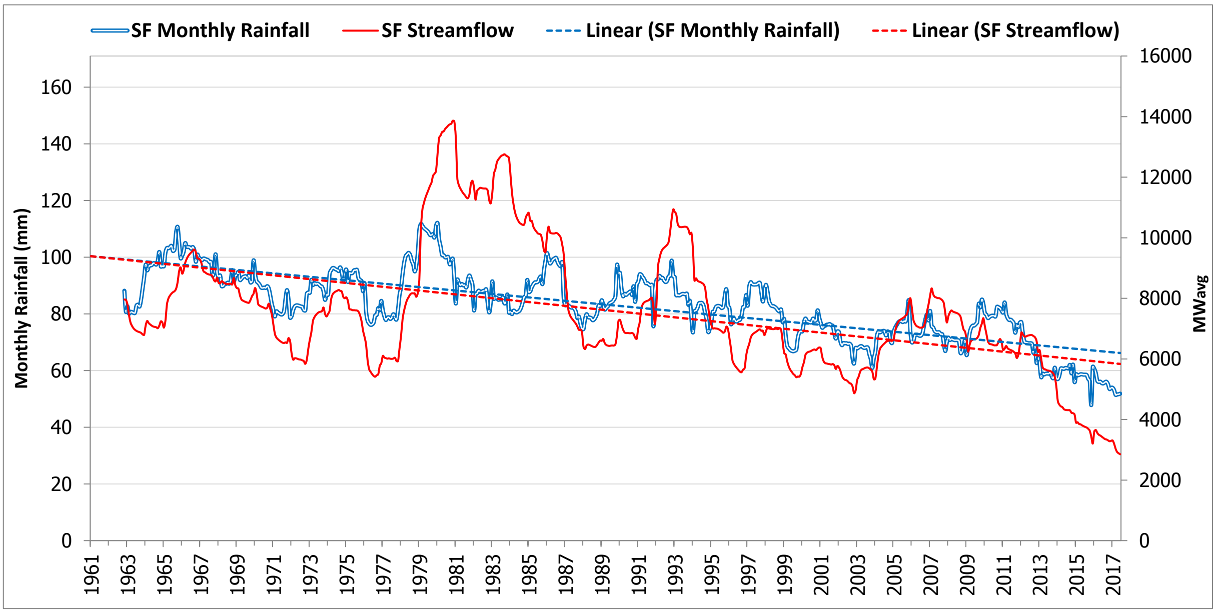

Figure 8: 24 month rolling average of the São Francisco (SF) basin's monthly rainfall (mm - LHS axis) and natural power / streamflow (MW$_{avg}$ – RHS axis) from 1961-2017. Sources: ONS (2017) and CPTEC/INPE (2017).

From 1961-2017 a strong correlation of 0.81 was observed between monthly streamflow and rainfall data for the São Francisco basin, allowing for the fact that peaks in streamflow in the lower-middle São Francisco River typically occur approximately 1 month after peaks in rainfall. However, the relationship between rainfall and streamflow is non-linear due to infiltration, evaporation and irrigation. The change in the hydrology balance in a reservoir can be determined from the following formula:

${}^{dV}\!/_{Dt} = I - Q - E_o \cdot A + P \cdot A$; where V is the reservoir volume, I is the inflow rate of the reservoir, Q is the outflow rate of the reservoir, E_o is the evaporation rate, P is the precipitation rate and A is the area of the reservoir (ONS, 2004). The annual evaporation from the principal reservoirs in the São Francisco basin (Três Marias, Sobradinho and Itaparica) was calculated from net evaporation data estimates obtained from the ONS (2004).

Hydroelectric power production can be derived from the following formula:
$P = \rho \cdot g \cdot H \cdot Q$; where P (W) is power, ρ is the density of water, g is the gravitational constant, H (m) is head height and Q (m^3/s) is the water flow rate.

Assuming that the average annual head height in all the São Francisco reservoirs remains relatively constant, the NE's annual average hydroelectricity production will be roughly proportional to the annual streamflow through the São Francisco basin.[3] To demonstrate the non-linear relationship between rainfall and streamflow, average annual rainfall and streamflow data as well as hydroelectric availability from 1996-2016 is shown graphically.

The state of the water resources and hydroelectric production in the NE region by the end of the century will be estimated by analysing the long-term rainfall reduction projections as a result of climate change together with historical data for rainfall and streamflow. In particular, the effects on streamflow as a result of the drought experienced in the São Francisco basin during the last 5 years are compared to the streamflow during non-drought periods. It is anticipated that analysing the impact of drought on the São Francisco basin can also give some foresight on the conditions and flow of the river by 2100.

4. DISCUSSION OF RESULTS

It is interesting to estimate the impact that a reduction of 35% in rainfall would have on the São Francisco river flow rates and hydroelectricity generation. In a first scenario it is assumed that water streamflow is directly proportional to rainfall and that a reduction in river flow is directly proportional to reduction in rainfall. Therefore, by the end of this century it is

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[3] While it is possible to maintain the average head height of the São Francisco reservoirs close to their long-term means by regulating electricity generation to the corresponding reductions in water streamflow, in recent years as a result of drought this has not happened because the marked reduction in rainfall has meant that reservoir levels in the Sobradinho and Três Marias reservoirs which have seasonal storage, have not been replenished during the wet season. Therefore, the reduction in average power flow data from the ONS for these dams may be significantly amplified relative to the reduction in average streamflow.

estimated that the average annual hydroelectric output power (MW_{avg}) will drop by approximately 35% compared to the average output at the end of the 20th century.

It can be observed from the linear trend-lines in figure 8 that monthly rainfall and power / streamflow in the São Francisco basin decreased approximately 0.58mm (0.65%) and $67MW_{avg}$ (0.79%) per year, respectively, since the 1980s. In fact, relative to the long-term average baselines, rainfall and streamflow have already declined by 25% and 33%, respectively, as can be observed in table 1. This historical data already demonstrates that streamflow is declining faster than rainfall. Projected reductions of these parameters can also be observed in table 1, assuming a linear extrapolation of the trend-lines in figure 8. A linear extrapolation of the rainfall trend-line from 1961-2017 is assumed because the IPCC B2 projection of rainfall reductions in the São Francisco basin shown in figure 6 (MARENGO et al, 2012) is roughly linear with time (see figure 9 which shows various trend-line alternatives for rainfall in the São Francisco). Furthermore, in the B2 scenario projections, the increase in both global temperature and the cumulative CO_2 concentration in the atmosphere are also roughly linear. Nevertheless, the further into the future climate projections are made, the more uncertainty there is, especially with rainfall projections. In addition, figure 9 shows that annual rainfall has been below its 1961-1990 long-term average every year since 1997.

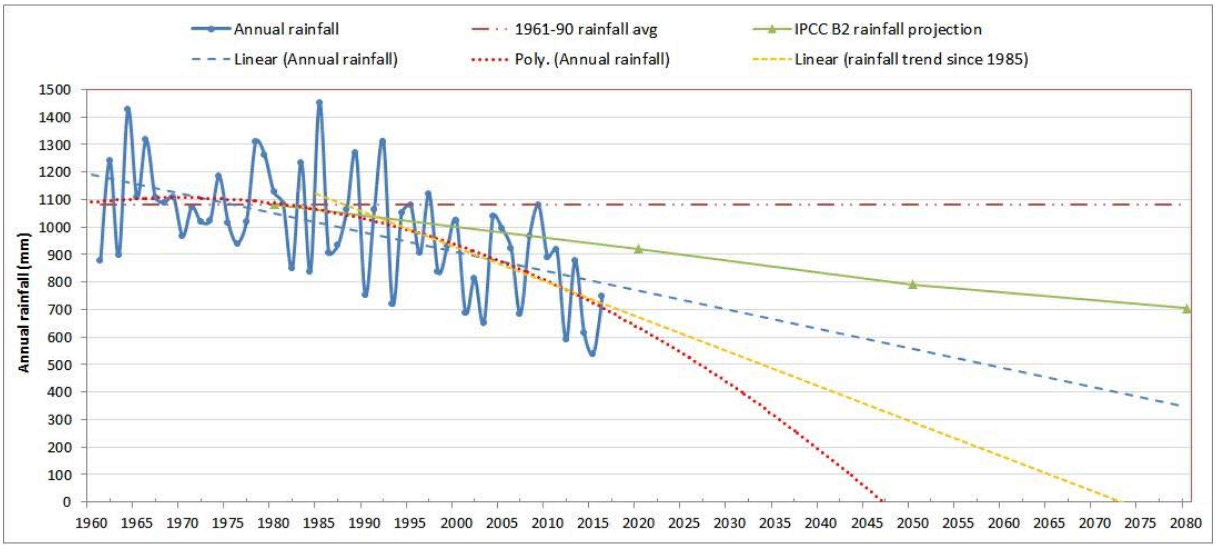

Figure 9: Annual rainfall (mm) in the São Francisco basin from 1961-2017 and various trend-line alternatives extrapolated into the future. Sources: CPTEC/INPE (2017) and Marengo et al (2012). Note, the downward trends of annual rainfall from 1961-2017 and from 1985-2017 were confirmed using the Seasonal Mann-Kendall Test.

It can also be observed in figure 8 that average rainfall from 2012-2016 dropped below 60mm per month as a result of an extended drought. According table 1, by 2030 average rainfall (during not drought periods) is projected to drop by 34% to 60mm/month, therefore, the low rainfall levels experienced during the last 5 years could become the norm by as early as 2030.

Table 1: Reduction in monthly rainfall and streamflow in the São Francisco basin relative to long-term averages.

	Rainfall	Rainfall reduction relative to 1961-90 avg:		
Year	(mm)		(mm)	(%)
1961-90	***90.2***	*Decrease per year*	*0.58*	*0.65%*
1995	80.0	Decrease in 20 years	10.2	11.3%
2016	67.8	Decrease in 41 years	22.4	24.9%
2030	*59.6*	*Decrease in 55 years*	*30.6*	*33.9%*
2050	*47.9*	*Decrease in 75 years*	*42.3*	*46.9%*
2085	*27.5*	*Decrease in 110 years*	*62.7*	*69.5%*
2100	*18.7*	*Decrease in 125 years*	*71.5*	*79.2%*

	Streamflow	Streamflow reduction relative to 1931-90 avg:		
Year	(MWavg)		(MWavg)	(%)
1931-90	***8500***	***Decrease per year***	***67***	***0.79%***
1995	7144	Decrease in 20 years	1356	16.0%
2016	5735	Decrease in 41 years	2765	32.5%
2030	*4796*	*Decrease in 55 years*	*3704*	*43.6%*
2050	*3454*	*Decrease in 75 years*	*5046*	*59.4%*
2085	*1106*	*Decrease in 110 years*	*7394*	*87.0%*
2100	*100*	*Decrease in 125 years*	*8401*	*98.8%*

Linearly extrapolating rainfall reduction in the São Francisco basin from 1961-1990 to 2071-2100 (110 years) according to figure 8 and table 1, would see a reduction of approximately 70% which is at least double the projections from Marengo et al (2012) and Lucena et al (2009) and substantially more than the projections from Marengo, (2008a) and Marengo et al (2009). Hence, three different rainfall reduction scenarios are used in this study.

Because average rainfall dropped below 60mm per month during the last 5 years of drought, in 2015 the average annual streamflow in the São Francisco basin dropped below 3500MW_{avg} and is continuing to drop. Given the linear projection of average rainfall for 2030 is 60mm per month (see table 1), it could be concluded that under non-drought conditions average streamflow will drop below 3500MW_{avg} by 2030. This is a reduction of almost 60%, yet the extrapolated streamflow data shown in table 1 suggests that average streamflow will not drop below this level until 2050. However, the reduction in streamflow can actually be substantially amplified relative to a reduction in rainfall, particularly in semi-arid environments (SAFT et al, 2015 and TIMBAL et al, 2015).[4] According to David Ferran (IHU On-line, 2016), during years with normal rainfall approximately 10% of rainfall reaches the NE reservoirs, however, during drought years (e.g. 2012-2014) initially only about 1% of rainfall reaches the reservoirs. During years of low rainfall, the efficiency of rainfall reaching the reservoirs is much lower because after a period without rainfall the first rains are mostly absorbed by the soil (via infiltration) and only once the soil drenches can water more effectively flow into the larger reservoirs.

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[4] Therefore, the linear extrapolation of streamflow into the future shown in table 1 is purely demonstrative and henceforth these projections should be disregarded.

The São Francisco basin is already irrigated extensively for agriculture, particularly in northern Bahia on the border with Pernambuco (SILVA, 2004) and in the far west of the state of Bahia. The CBHSF (2016) estimated that from the year 2000 until 2010, the amount of water removed from the river for irrigation and urban/industrial uses more than double. In 2013, on average 216 m^3/s of water was diverted and consumed, 90% of which was for irrigation (CBHSF, 2016). This equates to 7.5% of the São Francisco river's long-term average streamflow from 1931-1990, however, this figure equates to 20% of the depleted average streamflow in 2015. Additionally, with the planned transposition of the river (MARENGO, 2008b), it is expected that in the future its water resources will be increasingly used for irrigation. Furthermore, more reservoir water may be lost to evaporation and ground infiltration as a result of higher air temperatures, lower humidity and stronger winds that are projected for the semi-arid region. Based on the ONS evaporation estimates, it was calculated that approximately $950MW_{avg}$ are lost to evaporation annually, which equates to 11% of the São Francisco river’s long-term average streamflow from 1931-1990. However, based on the diminished average streamflow in 2015, it is estimated that the same quantity of evaporation losses equate to approximately 30% of the river’s streamflow for that year.

Therefore, in relation to a reduction in rainfall, the drop in average streamflow for hydroelectric generation is likely to be even more drastic. For example, considering that the average long-term rainfall in the São Francisco basin is 1083mm per year, it was estimated that 905mm, 17mm, and 11mm are typically lost due to infiltration, reservoir evaporation and irrigation, respectively. This leaves approximately 150mm of rainfall for hydroelectric generation. However, in 2016, average annual rainfall was only 749mm, which is 31% below the long-term average. Assuming that roughly the same gross amounts of annual rainfall were lost to evaporation and irrigation, it was estimated that 660mm of rainfall was lost due to infiltration. As a result there was only 61mm of annual rainfall for hydroelectric generation which is a reduction of almost 60% compared to the long-term average.

In fact, Saft et al (2015) and Timbal et al (2015) explain that due to non-linear hydrologic processes, the reduction in streamflow can be magnified relative to rainfall and is typically 2-3 times the magnitude of the decline seen in rainfall. This ratio of proportional changes between precipitation and streamflow is known as the elasticity factor. The elasticity phenomenon in the semi-arid region of the NE can be observed in figures 10 and 11, where the decline in the São Francisco basin streamflow is more extreme when compared to the drop in rainfall from

2011-2015. It can be observed in figure 10 that rainfall was slightly below its long-term average from 2012 to 2014, but the São Francisco streamflow was substantially below its long-term average. Moreover, the slope of the streamflow trend-line shows a far more drastic decline than the slope of the rainfall trend-line.

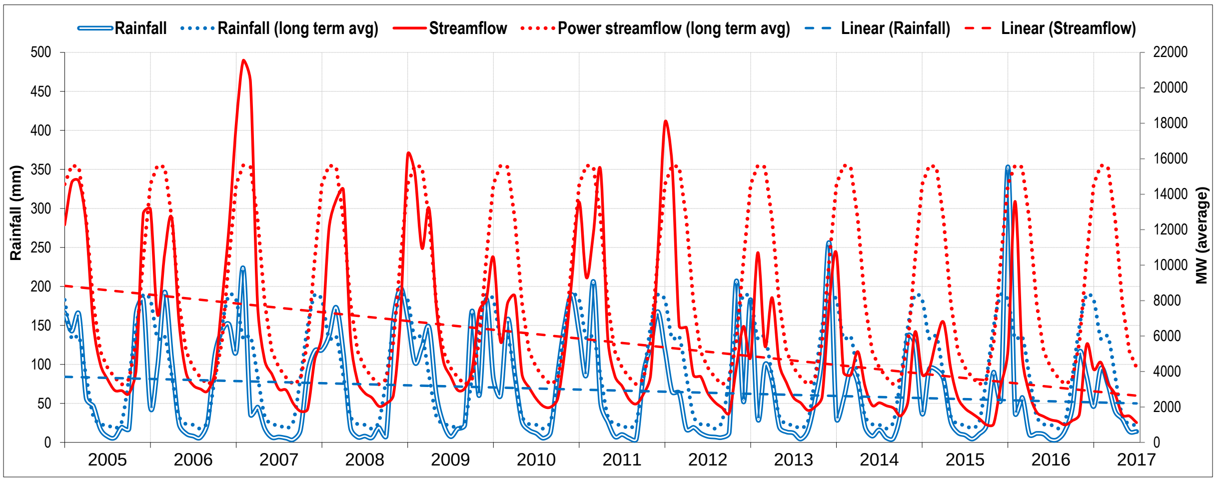

Figure 10: Monthly rainfall (mm - LHS axis) in the São Francisco basin and monthly power / streamflow (MW_{avg} – RHS axis) from 2005-2017. Sources: ONS (2017) and CPTEC/INPE (2017).

Specifically, it was observed that rainfall from 2013 to 2016 was approximately 36% below the long-term average, while the São Francisco streamflow in 2015 and 2016 was almost 62% below its long-term average. Furthermore, in 2016 rainfall was approximately 31% below the long-term average, while the São Francisco streamflow was almost 60% below its long-term average. Therefore, in the second scenario an elasticity factor ranging from 1.7 to 2 is assumed. Hence a reduction in rainfall of 35% could see a reduction in streamflow and average annual power of 60% or more. Therefore, it is estimated that the predicted decline in rainfall of 35% by 2100 could result in a reduction of at least 60% in the NE's annual average hydroelectric generation. According to the above results, by 2100 the NE's average hydroelectric output could drop to less than 40% of its average output at the end of the 20th century.

Likewise, considering a more conservative rainfall reduction forecast of only 20%, the corresponding reduction in hydroelectricity generation would be at least 34%. However, considering a rainfall reduction forecast of 50%, with an elasticity factor of 2, would suggest that streamflow and hydroelectric generation in the lower-middle São Francisco basin would be reduced to virtually zero and the river could dry up before reaching the sea. While it may not be valid to apply an elasticity factor of 2 to very high rainfall reduction projections such as

50%, if the São Francisco River is over exploited during the next 50-80 years, the lower basin could run dry or experience very high levels of salinity due to substantially reduced streamflow. This has already happened to a number of other major rivers around the world, such as the Colorado River which runs dry well before reaching the sea (HOWARD, 2014 and BROWN, 2006). Moreover, reservoir levels and hydroelectric generation along the Colorado River are also threatened by reduced runoff due to climate change and increasing human water consumption (BARNETT & PIERCE, 2008). The impact of droughts on the average monthly rainfall and streamflow in the São Francisco basin as well as hydroelectric availability and generation from 1996-2016 is shown in figure 11.

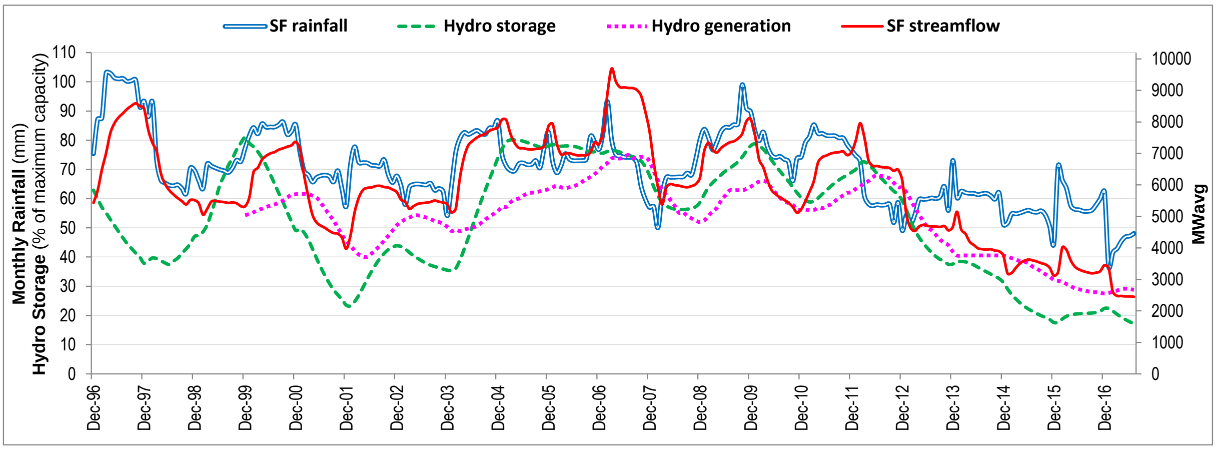

Figure 11: 12 month rolling average plot of rainfall (mm - LHS axis), hydro storage (% of maximum capacity), hydro generation MW_{avg} – RHS axis) and average power / streamflow (MW_{avg} – RHS axis) in the São Francisco basin from 1996-2016. Sources: ONS (2017) and CPTEC/INPE (2016).

As a result of these droughts, it was calculated that the average annual flow measured in terms of average annual power (MW_{avg}) dropped to 47%, 44% and 37% in 2001, 2014 and 2015, respectively, in relation to the river's long-term average flow from 1931-1990 (ONS, 2017). The average streamflow for the last 12 month ending 31 July 2017 was only 29% of the long-term average and in 2016 hydroelectric plants in the NE subsystem operated with an average capacity factor of only 23% of their total installed capacity. Furthermore, it can be observed in figure 3 (and figure 11) that the average annual hydroelectric generation from 2005-2007 was approximately 55,700GWh (6360MW_{avg}), but declined to approximately 47% and 40% of this value in 2015 and 2016, respectively. According to the above studies on predicted average rainfall in the São Francisco basin due to the impact of climate change, this type of reduction in energy output could become the norm by 2100. However, according to the linear extrapolation of rainfall in the São Francisco basin (shown in table 1), a reduction of 60% in the average annual hydroelectric generation and streamflow could actually occur by 2030.

As a result of severe drought conditions caused by inter-annual rainfall variations, the hydroelectric output could be reduced to less than 50% of the average output expected for a given year. Therefore, under severe drought conditions the hydroelectric output by the end of the century (or decades before) may be reduced to only 15-20% of what it was at the end of the 20th century. Clearly, during the coming decade, alternative sources of renewable energy (such as wind and solar power) need to be developed in order to replace the predicted lost hydroelectric production. Unlike the negative impacts projected for hydroelectricity, wind power potential in Brazil and particularly in the North and Northeast regions is predicted to increase considerably in the second half of the 21st century. Additionally, in figure 10 it was observed that streamflow in the São Francisco River is typically at its lowest level from June to November which is typically the period that wind energy generation is at its highest.

5. CONCLUSION

As a result of more extreme weather events expected across Brazil, there will be an increased risk of forest fires, particularly in the NE region, and the South and Southeast regions could suffer from more intense flooding. Furthermore, climate change projections and inter-annual weather variations could cause significantly reduced rainfall, more frequent droughts and higher temperatures in the North and Northeast regions of Brazil compared to the end of the 20th century. These impacts will negatively affect communities that depend on food, agriculture and biomass production in all regions of Brazil. One of the consequences for the NE region is that irrigation in the São Francisco basin is likely to increase to compensate for lost rainfall. The predicted reduction in rainfall together with an expected increase in irrigation will mean there is even less water available for hydroelectric production. Based on the IPCC B2 scenario projection, it is estimated that there will be a decline in rainfall of 35% by 2100 and this could result in a reduction of at least 60% in the NE's annual average streamflow and resulting hydroelectric generation.

However, linearly extrapolating the rainfall reduction in the São Francisco basin suggests that average rainfall could decrease by approximately 34% by 2030 and 47% by 2050 compared to the 1961-1990 baseline average. In effect, the rainfall estimates for 2100 based on IPCC B2 and A2 projections could actually eventuate as early as 2030 and 2050, respectively. Therefore average streamflow could decrease by approximately 60% by 2030 and up to 80% by 2050 compared to the 1931-1990 baseline average. In short, the deficits in rainfall and streamflow experienced during the last 3-5 years, as a result of severe drought, could become the norm by the 2030s. Therefore, by the 2030s the reduced streamflow in the São Francisco will limit hydroelectricity generation to only supply approximately 10-15% of the NE’s growing electricity demand. A consequence of these climatic changes during the coming decades is that the São Francisco River will become more important for urban and industrial water supplies, irrigation, livestock farming and local communities.

Even considering the more conservative IPCC B2 projection of rainfall by 2100, under severe drought conditions the drop in streamflow could still be as much as 85% compared to the streamflow during non-drought years at the end of the 20th century and from 2004 to 2012. Hence, at the end of the 21st century under severe drought conditions, hydroelectric production could drop to only 15% of the average production from 2004 to 2012. This loss in electricity generation will be largely supplemented by wind power in the NE region, which is already cheaper than electricity generated from fossil fuel, biomass and nuclear sources (DE JONG et al, 2015).

Wind power is expected to contribute approximately 55-57% of the NE’s electricity by 2020 (DE JONG et al, 2016 and DE JONG et al, 2017) and by the end of the 21st century wind power generation potential, as a result of stronger average winds, is predicted to increase substantially. Nevertheless this is assuming that existing wind corridors in the NE region today do not shift significantly as a result of climate change. Given that wind farms are built in wind corridors based on historical wind speed data, further research is required to examine if these wind corridors will shift as a result of changing climate cycles.

Future work could also simulate future streamflow of the lower-middle São Francisco including detailed irrigation, evaporation and infiltration data along the course of the river considering different annual rainfall and temperature scenarios. Additionally, more research needs to be conducted on short term and long-term solutions to water shortages in semi-arid regions. Specific solutions for the NE region might include more efficient water distribution and irrigation techniques, treatment of sewage for agricultural use, switching to crops more resilient to climate change induced drought, improved long-term weather and runoff forecasting, water use education, afforestation and revegetation of riparian zones and reforestation in water source areas.

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7. REFERENCES

ANEEL – Agência Nacional da Energia Elétrica / Brazilian National Electricity Agency, BIG – Banco de Informações de Geração / Information Bank of Generation; 2015. Available at: http://www.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.asp Accessed on 26/08/2015

Barnett T P, Pierce D W. When will Lake Mead go dry? Water Resources Research 2008; 44, 3.

BDMEP – Banco de Dados Meteorológicos para Ensino e Pesquisa / INMET – Instituto Nacional de Meteorologia; 2017.

Brown L R. Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble. Chapter 3. Emerging Water Shortages: Rivers Running Dry. W. W. Norton, 2006. Available at: http://www.earth-policy.org/?/mobile/books/pb2/pb2ch3_ss3/ Accessed on 03/11/2016.

CBHSF – Comitê da Bacia Hidrográfica do rio São Francisco. Resumo Executivo do Plano de Recursos Hídricos da Bacia Hidrográfica do rio São Francisco 2016-2025. CBHSF. Alagoas, 2016. Available at: http://cbhsaofrancisco.org.br/planoderecursoshidricos/wp-content/uploads/2015/04/RF3_24jan17.pdf Accessed on 03/04/2017.

CHESF – Companhia Hidreletrica do São Francisco. Vazão do rio São Francisco é reduzida. Notícias, Sistema CHESF; 2017. Available at: https://www.chesf.gov.br/_layouts/15/Chesf_Noticias_Farm/Noticia.aspx?IDNoticia=183 Accessed on 03/08/2017.

CPTEC/INPE - Centro de Previsão de Tempo e Estudos Climáticos / Instituto Nacional de Pesquisas Espaciais; 2017.

de Jong P, Sánchez A S, Esquerre K, Kalid R A, Torres E A. Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the Northeast region of Brazil. Renewable and Sustainable Energy Reviews 2013; 23: 526–535.

de Jong P, Kiperstok A, Torres E A. Economic and environmental analysis of electricity generation technologies in Brazil. Renewable and Sustainable Energy Reviews 2015; 52: 725–739.

de Jong P, Kiperstok A, Sanchez A S, Dargaville R, Torres E A. Integrating Large Scale Wind Power into the Electricity Grid in the Northeast of Brazil. Energy 2016; 100: 401-415.

de Jong P, Dargaville R, Silver J, Utembe S, Kiperstok A. Torres E A. Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid. Applied Energy 2017; 195: 538–555.

Genz F, Tanajura C A S. Trends and variability of climate and river flow in the region of Costa das Baleias, Brazil. Water Science & Technology 2013; 67 (1) 47-54.

Howard B C. 8 Mighty Rivers Run Dry From Overuse. National Geographic; 2014. Available at: http://environment.nationalgeographic.com/environment/photos/rivers-run-dry/ Accessed on 03/11/2016.

IHU On-line. Depois de cinco anos de seca no Nordeste, a possibilidade de um colapso é significativa. Entrevista especial com David Ferran. Instituto Humanitas Unisinos – IHU; 2016. Available at: http://www.ihu.unisinos.br/562171-depois-de-cinco-anos-de-seca-no-nordeste-a-possibilidade-de-um-colapso-e-significativa-entrevista-especial-com-david-ferran-versao-2 Accessed on 30/11/2016.

IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 2013.

Lucena A F P, Szklo A S, Schaeffer R, Dutra R M. The vulnerability of wind power to climate change in Brazil. Renewable Energy 2010; 35: 904-12.

Lucena A F P de, Szklo A S, Schaeffer R, Souza R R De, Borba B S M C, Costa I V L da, Júnior A O P, Cunha S H F da, The vulnerability of renewable energy to climate change in Brazil. Energy Policy 2009; 37: 879-889.

Marengo J A, Nobre C A, Salati E, Ambrizzi T. Mudanças climáticas globais e seus efeitos sobre a biodiversidade: Caracterização do clima atual e definição das alterações climáticas para o território brasileiro ao longo do Século XXI, Sumário Técnico. MMA - Ministério do Meio Ambiente, 2007. Available at: http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/prod_probio/Sumario.pdf Accessed on 30/03/2017.

Marengo, J A. Mudanças climáticas globais e seus efeitos sobre a biodiversidade: caracterização do clima atual e definição das alterações climáticas para o território brasileiro ao longo do século XXI / José A. Marengo – Brasília: MMA - Ministério do Meio Ambiente, 2007. 2a edição. Available at: http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/prod_probio/Livro2_completo.pdf Accessed on 30/03/2017.

Marengo J A, Ambrizzi T, Alves L M, Nobre C A, Pisnitchenko I. Atlas de Cenários Climáticos Futuros para o Brasil (Versão 1.0) Projeções climáticas (precipitação e temperatura) para o Brasil durante a segunda metade do Século XXI usando modelos regionais, nos cenários de baixas emissões (otimista IPCC-B2) e de altas emissões (pessimista IPCC-A2). MMA. Cachoeira Paulista, SP Fevereiro 2007. Available at: http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/prod_probio/Atlas.pdf Accessed on 30/03/2017.

Marengo J A. Regional Climate Change Scenarios for South America-The CREAS project. Conference on Climate Change and Official Statistics, Oslo Norway, 2008a.

Marengo J A. Water and Climate Change. Estudos avançados 2008b; 22: 63.

Marengo J A, Chou S C, Kay G, Alves L M, Pesquero J F, Soares W R, et al. Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. Climate Dynamics 2012; 38: 1829–1848.

Marengo J A, Jones R, Alvesa L M, Valverde M C. Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system. International Journal Of Climatology 2009; 29: 2241–2255.

Marengo J A, Bernasconi M. Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections. Climatic Change 2015; 129: 103–115.

Marengo J A, Torres R R, Alves L M. Drought in Northeast Brazil—past, present, and future. Theoretical and Applied Climatology 2016; vol 124, nos. 3-4.

Neto A R, da Paz A R, Marengo J A, Chou S C. Hydrological Processes and Climate Change in Hydrographic Regions of Brazil. Journal of Water Resource and Protection 2016; 8: 1103-1127.

ONS – Operador Nacional do Sistema Elétrico. Históricas da Operação - Geração de Energia; 2017. Available at: http://www.ons.org.br/historico/geracao_energia.aspx Accessed on 16/03/2017.

ONS – Operador Nacional do Sistema Elétrico. Plano da Operação Energética – PEN 2012 VOL. I – Relatório executivo RE 3/0146/2012; 2011. Available at: http://www.ons.org.br/download/avaliacao_condicao/operacao_energetica/PEN%202012_VOL1_RELATORIO%20EXECUTIVO.pdf Accessed on 16/01/2016.

ONS – Operador Nacional do Sistema Elétrico. Representação das defluências das usinas do Rio São Francisco nos estudos de planejamento e programação da operação. Notícias 01/11/2016; 2016. Available at: http://www.ons.org.br/sala_imprensa/2016nov01-defluencia_saofrancisco.aspx Accessed on 21/11/2016.

ONS – Operador Nacional do Sistema Elétrico. Evaporações líquidas nas usinas hidrelétricas - RE 3/214/2004; 2004. Available at: http://www.ons.org.br/operacao/rel_evaporacao.aspx Accessed on 21/11/2016.

Pereira E B, Martins F R, Pes M P, da Cruz Segundo E I, Lyra A A. The impacts of global climate changes on the wind power density in Brazil. Renewable Energy 2013; 49: 107-110.

PSR. Adaptação às mudanças climáticas no Brasil: cenários e alternativas - Energia. PPE/COPPE/UFRJ, 2015.

Saft M, Western A W, Zhang L, Peel M C, Potter N J. The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective. Water Resource Research 2015; 51, 4: 2444–2463.

Scorah H, Sopinka A, Van Kooten G C. The economics of storage, transmission and drought: integrating variable wind power into spatially separated electricity grids. Energy Economics 2012; 34: 536–541.

Sillmann J, Kharin V V, Zhang X, Zwiers F W, Bronaugh D. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. Journal of Geophysical Research: Atmospheres 2013; 118, 4: 1716-33.

Silva V P R da. On climate variability in Northeast of Brazil. Journal of Arid Environments 2004; 58: 575–596.

Tanajura C A S, Genz F, Araujo H. Mudanças climáticas e recursos hídricos na Bahia: validação da simulação do clima presente do HadRM3P e comparação com os cenários A2 e B2 para 2070-2100. Revista Brasileira de Meteorologia ed. online; 2010. vol. 3. p. 345-58.

The World Bank. Low hydrology Scenario for the Brazilian power sector (2016-2030): Impact of climate on greenhouse gas emissions. Brasília: The World Bank, 2017. 132p.

Timbal B, Griffiths M, Tan K S. Rainfall and streamflows in the Greater Melbourne catchment area: variability and recent anomalies. Climate Research 2015; 63, 3: 215-232.

CHAPTER 2

Economic and environmental analysis of electricity generation technologies in Brazil

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Economic and environmental analysis of electricity generation technologies in Brazil.

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ABSTRACT

This study compares the economic viability of renewable energy technologies – wind, solar photovoltaic, concentrated solar thermal, biomass and wave power – to traditional generation technologies including hydroelectricity, nuclear power, coal power and gas power sources. The Levelised cost of Electricity (LCOE) for different generation technologies in Brazil are calculated by reviewing existing published literature and examining 13 case study projects. Initial results found that using a low (5%) discount rate, the hydroelectric plants had the lowest LCOE, but were only slightly cheaper than the wind power case studies. However, using a high (10%) discount rate, one of the wind power case studies actually had the lowest LCOE. Solar photovoltaic (PV) was found to be the most expensive technology followed by wave power and concentrated solar thermal power (CSP). It will be shown that grid connected distributed PV and concentrated solar thermal technology are largely undeveloped in Brazil due to the high price associated with importing solar power equipment into Brazil and also due to ineffective federal government policy. The environmental and social externality costs of fossil fuel plants and large scale hydroelectric dams (in the Amazon region) are also discussed. It will be demonstrated that wind power becomes the cheapest generation technology in Brazil, once all externality and transmission line costs are taken into consideration.

Keywords: Renewable Energy; Solar; Wind Power; Wave Power; Hydroelectricity; Levelised Cost of Electricity.

1. INTRODUCTION

With the increase in fossil fuel prices and the global concern to reduce greenhouse gases there is a growing demand to shift away from CO_2 producing fossil fuels to renewable energy sources for electricity generation. In Brazil, wind, wave and solar power have enormous potential. However, the shift to these renewable technologies appears to remain almost at a standstill despite the enormous potential and their apparent viability in some locations.

In the past, poor economic viability together with a lack of reliable data and political willpower were obstacles that prevented large scale wind farms going ahead in Brazil [1]. But more recently, several large scale wind farm projects have been undertaken by private enterprise. These projects are now viable due to increasing fossil fuel prices, the local manufacture of wind turbines and the introduction of carbon credits through the Clean Development Mechanism [2, 3]. The Northeast region (NE) of Brazil, in particular, has excellent solar energy potential. However, due to the high costs to import solar power equipment and the lack of government incentives, there are very few utility scale solar power projects installed in Brazil [2, 4].

Despite the huge potential, there is still an apparent lack in the development of large scale wind, solar and wave power technologies. Therefore, the objective of this study is to analyse the economic and environmental viability of these developing renewable energy technologies in Brazil and compare them to more traditional generation technologies. Specifically, the Levelised Cost of Electricity (LCOE), which is used to benchmark the economic viability of different electricity generation technologies, is calculated for 13 different case study plants following the NEA-IEA-OECD [5] methodology. It is anticipated that the results of this study will assist energy planners to make more objective and informed decisions regarding new electricity generation projects.

All the case study plants will be connected or are already connected to the Brazilian electricity grid. Given the particular energy generation challenges faced by the Northeast region (NE) (see section 1.2) and the region's enormous wind and solar energy potential (see section 1.3), the majority of the case studies chosen are within the NE.

This work also aims to examine the environmental and social impacts of traditional generation technologies in Brazil by analysing those case studies that cause significant amounts of greenhouse gas (GHG) emissions, air pollution or that impact the environment in other ways. Where possible, the costs of these environmental and social externalities will be estimated in terms of health damage costs and greenhouse gas damage costs. Additionally the costs and energy losses of extended transmission line systems will be estimated for those case studies located in remote areas such as the Amazon. The advantages and disadvantages of small scale distributed renewable energy systems are compared to large scale centralised power plants with extensive transmission systems.

1.1. The Brazilian electricity sector

The electricity supply matrix for Brazil consists of 62.5% hydroelectricity, about 5.7% imported power which is mostly hydroelectricity, 8.6% biomass, and 3.9% wind power. Therefore, more than 80% of electricity generation is from renewable energy sources [4]. Brazil compares very well to the rest of the world, where on average renewable energy sources account for only 19.5% of electricity generation [6]. However, the capacity of hydroelectric generation is close to its maximum in most industrialized regions. There are unexploited water resources in the remote Amazon and Cerrado river basins. Nevertheless, large hydroelectric projects in these regions will have high environmental and transmission line costs, and relatively low energy density [7].

1.2. The Northeast region of Brazil

While Brazil overall has the world's largest water resources, the Northeast (NE) region is mostly semi-arid receiving only a small percentage of the annual total national rainfall. The region suffers from frequent droughts (the most recent in 2012), which can also affect the power supply, as the majority of the electricity matrix is supplied by hydroelectricity [3]. Additionally, by the second half of this century higher temperatures and reduced rainfall are predicted for the Brazilian North and NE regions due to Global Warming. These climatic changes will threaten hydroelectricity production [8], while wind power potential in these regions is predicted to double by 2070 [9].

Large hydroelectric potential in the Northeast (NE) region is entirely saturated. The São Francisco Basin, the largest water resource in the NE, already has five hydroelectric dams and it is no longer possible to build large hydroelectric facilities. As a result of drought in 2013 the NE region imported over 25% of electricity from the North and Southeast regions [10] as shown in figure 1. Therefore, the NE region will be faced with a number of challenges in order to maintain electricity supply with growing demand in consumption (approximately 4% per year) expected during the coming decades.

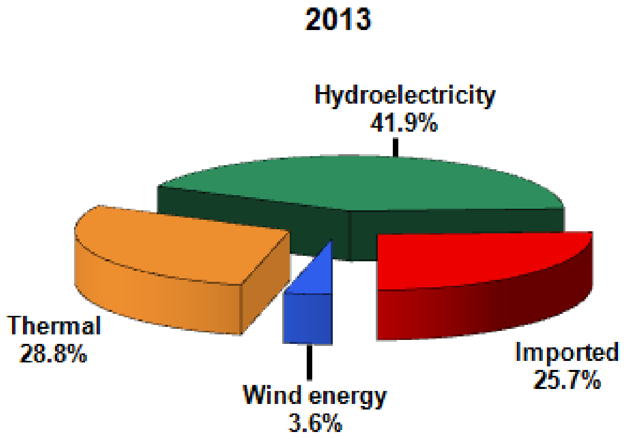

Figure 1: Origin of electricity consumed in the NE region for 2013. (Currently in the NE, "Thermal" electricity generation is from fossil fuels and biomass. "Imported" consists mostly of hydro from other regions). Source: ONS [10].

The construction of the huge Belo Monte hydroelectric plant, in the northern state of Pará, once completed, will allow for an increase of imported electricity from the North region, but with significant amounts of energy loss due to extraordinarily long transmission lines. Additionally, large hydroelectric dams, such as Belo Monte, planned for the Amazon basin have limited power output during the dry season and cause significant environmental conflicts.

Rather than rely on the current trend of importing electricity and constructing new fossil fuel power plants [11] it would be more sustainable and a cleaner alternative to invest in large scale renewable energy generation, given that the NE region is privileged with excellent solar and wind resources. The Northeast states of Bahia, Ceará and Rio Grande do Norte have already experienced a rapid growth in wind farm deployment due to favourable conditions in terms of wind speed, frequency, distribution and turbulence, but there is potential for a great deal more development.

1.3. Brazilian Wind and Solar energy potential

The onshore wind power potential in Brazil (at 50m above ground level) is approximately 145,000MW, and more than half of this potential is in the NE region, according to the Brazilian Atlas of Wind Power Potential [12].

The annual average daily solar radiation (on an inclined plane) for the Northeast region of Brazil is 5.9kWh/m^2, the highest solar resource potential in the country.[5] Grid-connected photovoltaic (PV) systems in commercial and urban areas could supplement the supply of daytime air-conditioning loads. There is also a huge potential for solar hot-water heating to replace inefficient electric hot-water showerheads which consume 24% of residential electricity across Brazil [14].[6] Furthermore, applications such as hybrid PV – diesel plants in the arid areas of the Northeast and in the Amazon, could provide cost effective electricity for remote villages that rely on expensive diesel generators [15].

However, in addition to high import duties, there is still a lack of government regulation and support policies, such as subsidies, tax incentives and defined pricing for solar and wind power development. Additionally these intermittent renewable resources are still at a disadvantage from other government barriers such as subsidies for fossil fuel consumption in remote areas like the Amazon [7, 15].

Until quite recently there were no suitable regulations for connecting PV (or other small generator) systems to the electricity grid and trading or reselling excess energy back to the electricity providers. However in April 2012, the *Agência Nacional da Energia Elétrica* (ANEEL) approved a resolution that allows consumer micro and mini installations of renewable sources (including PV) to be connected to the grid and exchange energy for credits with the local distributor [16].

2. VIABILITY OF RENEWABLE ENERGY LITERATURE REVIEW

2.1. International studies on the cost of generating electricity

Various international studies comparing the LCOE have been completed which include renewable technologies such as wind, solar PV and concentrated solar thermal power (CSP). For example a study published by the Melbourne Energy Institute [17] reviews data from a range of international and Australian studies projecting the LCOE of wind, photovoltaic and

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[5] Note that commercially available crystalline silicon PV modules typically have efficiencies of around 14% and system efficiencies such as inverter losses also need to be accounted for [13]. Therefore, the average daily energy output from a Solar PV system in the NE would be approximately 0.70-0.75kWh/m^2.

[6] Additionally, implementing the use of variable speed drives to control AC motors is an effective energy efficiency technology that could substantially reduce electricity consumption in the Brazilian industrial sector.

CSP generation technologies from 2010 until 2030. The overall trends of all the studies for all 3 technologies considered showed a decreasing LCOE. Specifically, according to the IEA curve, by 2030 the LCOE of wind power, PV and CSP is predicted to drop below $35/MWh, $50/MWh and $25/MWh, respectively. Similarly, studies by the Australian Academy of Technological Sciences and Engineering [18] and the U.S. Energy Information Administration [19] examine the projected LCOE of new generation technologies until 2040. However, results from these studies are country specific and the international LCOE estimates are not valid for Brazil.

The NEA IEA OECD [5] report has LCOE data comparing traditional generation technologies in Brazil and the results can be seen in figure 2.

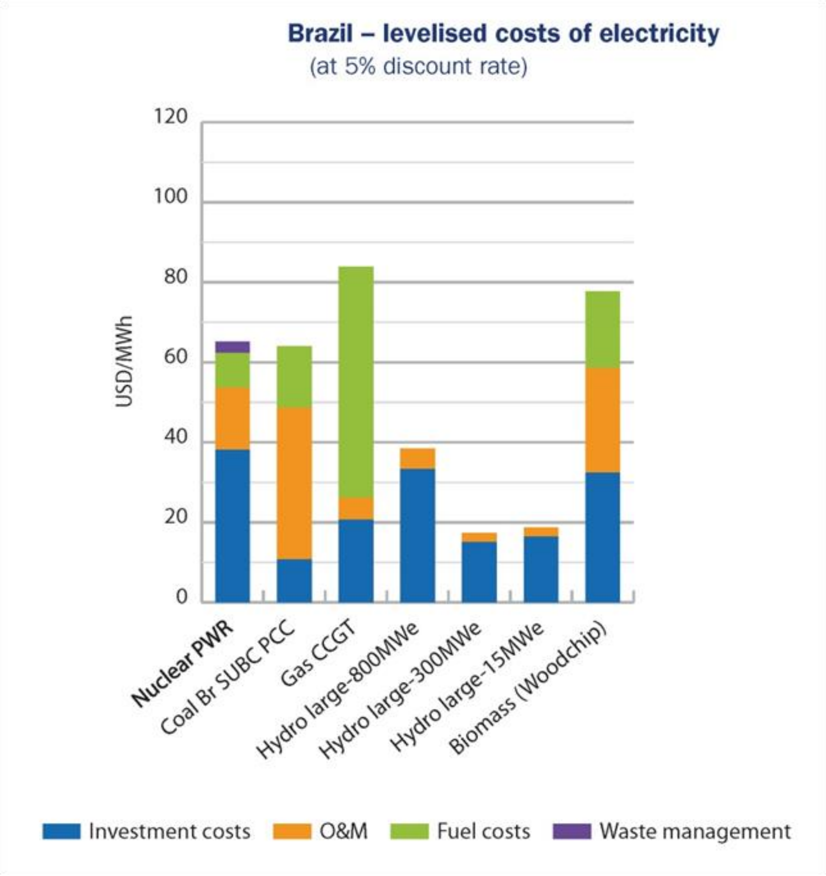


Figure 2: LCOE in Brazil. Key: PWR Pressurized water reactor; Br Brown coal; SUBC Subcritical; PCC Pulverised coal combustion; CCGT Combined cycle gas turbine. Source: NEA IEA OECD [5].

Unfortunately the graph in figure 2 does not show the LCOE for solar PV, concentrated solar thermal power (CSP) or wind power in Brazil. Apart from the above NEA IEA OECD [5] analysis which compares the LCOE of Brazil’s principal generation technologies, there have been almost no studies focussing on the cost of different electricity generation technologies in Brazil. Additionally the above graph does not consider the social and environmental externality costs of traditional generation technologies in Brazil. Therefore, this study aims to present a more complete analysis of the LCOE in Brazil by including previously omitted renewable technologies and environmental externalities.

Nicholson et al [20] in their article "*How carbon pricing changes the relative competitiveness of low-carbon baseload generating technologies"*, make a selective analysis of various authoritative economic studies on the LCOE and life-cycle assessment (LCA) of emissions for various generation technologies. However, the article omits several renewable energy technologies from the analysis, including hydroelectricity, biomass, geothermal, PV, wind and wave energy.

Allan et al [21] calculated the levelised costs of energy (electricity) for two marine energy technologies (Wave and Tidal Stream power) in the UK compared with ten other generation technologies (renewable and non-renewable). Unfortunately the study does not include any forms of solar electricity generation.

Liu et al [22] investigated the economic, technical and environmental performance of residential photovoltaic (PV) system in Queensland (Australia). As a result of feed-in-tariffs, at the end of 2013, there was a total capacity 3200MW of PV installed in Australia of which 95% is grid-connected [23]. By comparison, Brazil currently only has 15MW of PV connected to the national grid [4]. Australia has 200 times more PV installed than Brazil, a country with good solar resources and a population almost 10 times that of Australia.

Comparing all the results of the above international studies, it becomes apparent that the LCOE for a particular technology can vary very significantly depending on the country or region. Hence this study focuses specifically on Brazilian electricity power plants and aims to provide accurate LCOE data for Brazil.

2.2. Previous LCOE studies for the Brazilian electricity sector

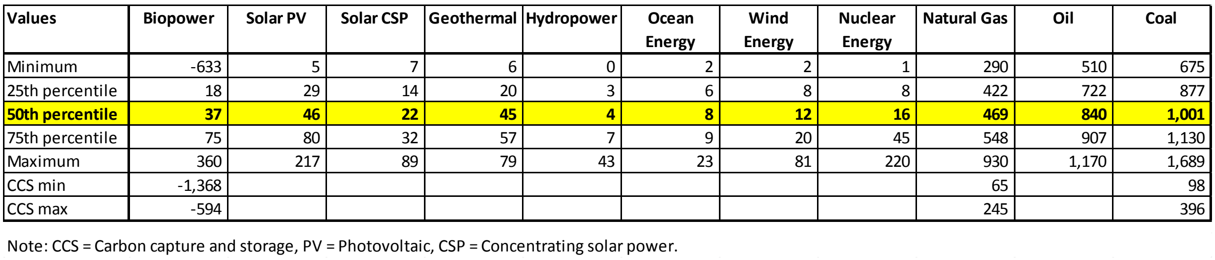
Solar energy in Brazil is greatly underutilized and there is huge potential to develop hybrid PV systems in isolated communities that currently rely on expensive diesel generators. Colle et al [24], presents a map of the *“...Life Cost Saving of Photovoltaic Diesel Hybrid Power Plant for Isolated Grids”* in Brazil demonstrating that huge life cost saving can be achieved compared to a diesel only generator. Similarly, Silva et al [15] show the economic viability of various PV hybrid distributed generation system configurations using PV, Fuel Cell (FC), battery and diesel technologies compared to diesel only electricity generation for remote communities in the Amazon.

There are almost no studies which specifically examine the LCOE for grid connected renewable technologies in Brazil. Cardemil and Colle [25] conducted one of the few studies examining the economic viability of a concentrated solar thermal power system in Brazil.

2.3. Environmental, social and transmission externality studies

Emission intensity factors can be obtained by making a life cycle assessment (LCA) of each generation technology in terms of kg of CO_{2eq} emitted per MWh produced. In the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) produced by The Intergovernmental Panel on Climate Change (IPCC) [26] a comprehensive analysis of emission intensity factors from different reference sources was completed. Table 1 shows the aggregated results of this literature review of life cycle assessments of GHG emissions (g of CO_{2eq}/kWh) from different electricity generation technologies.

Table 1: Aggregated results of literature review of LCAs of GHG emissions from various electricity generation technologies (kg CO_{2eq}/MWh). Source: IPCC [26].



Values	Biopower	Solar PV	Solar CSP	Geothermal	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Minimum	-633	5	7	6	0	2	2	1	290	510	675
25th percentile	18	29	14	20	3	6	8	8	422	722	877
50th percentile	**37**	**46**	**22**	**45**	**4**	**8**	**12**	**16**	**469**	**840**	**1,001**
75th percentile	75	80	32	57	7	9	20	45	548	907	1,130
Maximum	360	217	89	79	43	23	81	220	930	1,170	1,689
CCS min	-1,368								65		98
CCS max	-594								245		396

Note: CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.

The median (50th percentile) emission intensity factors can be used to calculate the contribution that carbon tariffs would have on the LCOE of coal, oil and gas fired power plants by multiplying them with, for example, the European Union carbon Allowances (EUAs) price or the UN-backed Certified Emission Reductions credits (CERs) price. Likewise carbon credits can be calculated for clean renewable energy projects that could be eligible for credits under the Clean Development Mechanism or similar carbon trading schemes. However, since a peak in the carbon price of €29/tonne of CO_2 in mid-2008, the EUA (and CER) tariffs have had several price crashes to lows of €3/tCO_2 and €0.25/tCO_2, respectively [27]. To date, carbon prices have not recovered rendering the trading schemes completely ineffective at reducing global emissions. Furthermore, as renewable energy projects have lifetimes in excess of 20 years, any benefits from fluctuating carbon credits for such projects cannot be reliably estimated. Additionally, given that Brazil's electricity and transport sectors have relatively low carbon footprints and that the majority of the country's emissions are from illegal deforestation, it is unlikely that carbon tariffs would be imposed in the foreseeable future. Therefore, in this paper, rather than considering the effects of carbon tariffs, the economic impact of environmental externalities on the LCOE will be estimated for different generation technologies.

There have been a number of studies that estimate the economic effects of climate change including the much debated Stern Review [28]. The most extensive study on the cost of environmental externalities in terms of GHG damage and health impact costs from power generation is the European Union's ExternE Project [29, 30]. The Australian Academy of Technological Sciences and Engineering (ATSE) [31] used the ExternE results [29] and applied them to the Australian electricity generation sector.

Alves and Uturbey [32] calculated the environmental externality costs of electricity generation in Brazil using various sources. For GHG damage costs their study also followed the ExternE methodology [30] for fossil fuel plants (applying a damage cost of \$25/tCO_{2eq}) and followed equations developed by the IPCC for hydroelectric plants. Fearnside [33] conducted a study which focussed specifically on the Belo Monte hydroelectric plant and conservatively estimated the GHG emissions caused by the Belo Monte and Babaquara dams. Applying the Alves and Uturbey [32] method to the Belo Monte and Babaquara dams results in a comparative prediction for the quantity of GHG emissions.

Delucchi and Jacobson [34] also review the US National Research Council´s estimates of environmental damage from fossil fuel electricity generation. The midrange estimate for the cost of GHG damage was \$30/tCO_{2eq} (20% more than the ExternE figure) and the impact of air pollution on human health from coal fired electricity generation had a mean cost of \$32/MWh (45% more than the ExternE estimate of \$22/MWh).

As well as reviewing the environmental damage from various energy technologies, Delucchi and Jacobson [34] include 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 [34].

3. MATERIALS AND METHODS

3.1. Economic analysis

In this study, the costs to produce electricity, measured in megawatt hours (MWh) of different generation technologies is compared using the levelised Cost of Electricity (LCOE) calculation following the methodology of the Nuclear Energy Agency (NEA), the International Energy Agency (IEA), and the OECD [5]. The formula is derived by assuming the Net Present Value of all the revenues equals the Net Present Cost of the entire project over the lifetime of the project as shown below [5]:

$$\Sigma_t(Electricity_t * P_{Electricity} * (1+r)^{-t}) = \Sigma_t((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t})$$

Then

$$\mathbf{LCOE = P_{Electricity} =}$$

$$\boldsymbol{\Sigma_t((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t}) / (\Sigma_t(Electricity_t*(1+r)^{-t}))}$$

Where:

$Electricity_t$: The amount of electricity produced in year "t";

$P_{Electricity}$: The constant price of electricity; (assumed to be stable and does not change during the lifetime of the project).

$(1+r)_{-t}$: The discount factor for year "t"; (the interest rate "r" is assumed to be stable and does not change during the lifetime of the project).

$Investment_t$: Investment costs in year "t";

$O\&M_t$: Operations and maintenance costs in year "t";

$Fuel_t$: Fuel costs in year "t";

$Carbon_t$: Carbon costs in year "t";

$Decommissioning_t$: Decommissioning cost in year "t";

The LCOE is calculated for real interest rates in Brazil. Using the real interest rate, allows for the effects of inflation. Using the FISHER EQUATION it can be assumed that the real interest rate is the nominal bank interest rate less inflation. This method assumes that fuel costs, as well as operations and maintenance (O & M) costs increase in accordance to the inflation rate.

The NEA-IEA-OECD [5] *"Projected Costs of Generating Electricity"* publication contains detailed financial cost data on various Brazilian electricity generation technologies. Therefore, this document was used as a source of information to obtain explicit O & M, decommissioning and fuel costs for the fossil fuel (coal and gas), nuclear and hydroelectric power station case studies.

Given that the Brotas de Macaúbas wind farm Project Design Document [35] presented very detailed technical and financial data, where applicable, this document was also consulted as a reference base to estimate the O & M costs for the other wind farm complex and the national emissions factor. This emissions factor is the quantity (in tonnes) of CO_{2eq} emissions avoided per MWh of electricity generated from renewable energy plants in Brazil.

3.2. Environmental social and transmission externality analysis

This study estimates the cost of social and environmental impacts from electricity generation based on data from existing literature. Specifically, following the method used by ATSE [31] this study uses the findings from the ExternE project [30] and applies them to the Brazilian case studies. It is assumed that the impact of global warming caused by GHG emissions is a global problem that on average will affect different continents in similar ways. Therefore, a GHG damage cost was estimated for those technologies that emit significant amounts of GHG. Similarly, assuming that the population density in the developed regions of Brazil is similar to that of Europe, this study also applies the results from the ExternE project [30] for health impact costs and applies them to the Brazilian "thermal" electricity generation case studies.

The annual quantity of GHG emissions caused by the Belo Monte hydroelectric dams and the Santo Antônio dam were estimated according to Fearnside [33] and Alves & Uturbey [32].

These annual GHG emission predictions were used to calculate the GHG damage costs per MWh following the ExternE [29, 30] and ATSE [31] methodology.

Extended transmission system losses and costs for the hydroelectric plants are estimates following the results by Delucchi and Jacobson [34]. The energy losses resulting from the extended transmission systems for both the Belo Monte and the Santo Antônio hydroelectric plants are calculated and the LCOE results for those plants are adjusted accordingly. That is, the total energy supplied to the existing distribution network is used to calculate the LCOE, rather than the total energy generated at the hydroelectric plant itself. The transmission systems investment costs are also calculated as a component of the LCOE in $/MWh. The additional transmission system costs for the hydroelectric plants in the Amazon, due to the extraordinary line lengths, are considered beyond the costs of conventional transmission systems. It is assumed that the other case studies are connected to the grid using conventional transmission lines which are much shorter and are often included in the capital investment of the project.

4. CASE STUDIES

4.1. Brazilian Renewable Energy Case Studies Within the NE Region

Brotas de Macaúbas Wind Farm

Brotas de Macaúbas is a 90 MW wind farm located in Chapada Diamantina in the central region of the state of Bahia. It consists of 57 wind turbines connected to the Brazilian National Interconnected grid System. The complex was commissioned in 2012 and supplies energy to the cities of Seabra, New Horizon and Macaúbas. The wind farm is predicted to have an operational capacity factor of 39.7%. The project built by Desenvix, had a total investment exceeding $190 million. Of all the projects analysed, Brotas de Macaúbas was the only project actually approved to receive carbon credits under the Clean Development Mechanism [35].

Caetité, Guanambi and Igaporã Wind Farms

In the interior of the state of Bahia, in the municipalities of Caetité, Guanambi and Igaporã, 14 wind farms consisting of 184 turbines began operating in July 2012. The complex of wind farms built by Renova has an installed capacity of 293.6MW (the largest installed wind power complex in Latin America to date) and cost approximately $580 million. The complex will produce an average of 134MW of power resulting in a high capacity factor (for wind energy) of 45.6% [36].

Tauá solar (PV)

The electricity generation company MPX, connected a large scale solar power plant to the national grid in August, 2011. This is the first PV plant of this scale to be installed in Brazil. The model plant is located at Tauá in the hinterland of Ceará, about 360 km from Fortaleza, on an area of 1.2 ha. In phase 1, it will generate up to 1 MWp at 13.8 kV with a 12 km transmission line, which is enough to serve approximately 1,500 families. With a capacity factor of only 18%, the Tauá PV system is extremely small relative to the production of hydroelectricity. The project had an investment of about $5 million [37, 38].

Pituaçu Solar

The photovoltaic system installed on the roof of the Pituaçu stadium in Salvador Bahia was commissioned in the first half of 2012. The 0.408 MWp project by the Electricity Company of the State of Bahia (COELBA) Neoenergia Group in partnership with the State Government of Bahia cost $2.3 million. The PV system is expected to produce 630 MWh of energy annually (resulting in a capacity factor of less than 18%). 56% of the total investment was for the equipment (642 mono-crystalline PV panels, 1652 amorphous silicon PV panels, 58 inverters and the control systems). The remaining 44% of the total investment was for installation and commissioning [39].

The guaranteed lifetime for mono-crystalline and amorphous silicon panels is 25 and 20 years, respectively, however given that PV panels can operate satisfactorily for several years beyond the manufacturer’s guarantee, a lifetime of 30 years was assumed for calculating the LCOE of both the Pituaçu Solar and Tauá solar projects.

Bioenergia (BEN) biomass power plant

Biomass energy plays an important role in the Brazilian electricity generation matrix with various raw materials used as fuel including bagasse (or sugar cane waste, which is the main biomass fuel in Brazil), black liquor, biogas, woodchip residue and rice hulls. Bioenergia (BEN) has recently installed a biomass cogeneration plant in Teotonio Vilela, in the state of

Alagoas which uses sugar cane bagasse to generate electricity and heat. The plant, which began operations in April 2013, has an installed capacity of 53 MW [4, 40] and the project had a total investment of approximately $92 million [40]. The capacity factor was assumed to be 85% (the same as for the coal fired power stations).

Bom Jesus da Lapa CSP (simulation)

Currently there are still no examples of CSP plants existing or under construction in Brazil. Thus, for this new technology, economic data was taken from the article entitled *"SWERA Database as support for techno-economic analysis of solar energy technologies"* [25]. The study conducted by the LEPTEN laboratory at the Federal University of Santa Catarina examined the economic viability of a 30 MWe parabolic trough reflector CSP system located in Bom Jesus da Lapa in the Northeast of Brazil using the SEGS VI plant configuration as reference. The model chosen for the analysis would have no thermal storage capabilities, therefore a conservative capacity factor of 20% was assumed.

4.2. Brazilian Hydroelectric Case Studies in the Amazon

Belo Monte hydroelectric power station

The Belo Monte hydroelectric power station is currently under construction on the Xingu River in the state of Pará. It is one of the most controversial power plants in Brazil, because of the project's social and environmental repercussions that will affect areas of the Amazon forest and local communities. With a nominal capacity of 11,233 MW, and a total investment estimated at $14.9 billion, Belo Monte will be the third largest hydroelectric plant in the world. However, as the Xingu River has a greatly reduced flow rate in the dry season, the plant will only produce an average of 4462 MW throughout the year, which represents a utilization (capacity factor) of only 39% of the total installed capacity [41, 42].

Santo Antônio hydroelectric plant

The Santo Antônio hydroelectric plant is located in the heart of the Amazon Basin on the Madeira River, about 10 km from Porto Velho in the state of Rondônia. The hydroelectric plant has an estimated total investment of $7.5 billion and will have an installed capacity of 3,150.4 MW. Once it is operating at full capacity it will produce more than 19.5 million MWh of electrical energy a year resulting in a capacity factor of 70% [43]. It is the first time that a hydroelectric plant with a low head (less than 20m) has been built in the Amazon basin. The plant will use bulb turbine technology which will allow for a type of large scale “run of river” electricity generation.

4.3. Brazilian Fossil Fuel and Nuclear Energy Case Studies

Angra-3 Pressurised water reactor (PWR) nuclear reactor

Angra 3 nuclear power station, located in Angra dos Reis in the state of Rio de Janeiro, will be Brazil’s third and largest nuclear reactor. The installed capacity of the plant will be 1,405 MW and the estimated cost of the project is $5 billion. The reactor is expected to produce 10,000 million kWh of energy annually resulting in a capacity factor of 81%. Originally work on the project began in 1984, but the development was halted in 1986 due to a lack of funding. Construction began again in 2010 and the reactor is expected to go into operation in December 2015 [44].

Energia Pecém - Coal power station

The Energia Pecém fossil fuel power plant is a 720 MW capacity coal fired power station being constructed by MPX Energy located in the municipality of São Gonçalo do Amarante 60km from Fortaleza in the state of Ceará (NE region). The project has a total investment of $1.4 billion and will feature two 360 MW turbine modules. Using pulverized coal imported from Colombia to the Port of Pecém, the entire plant will operate with a capacity factor of 85% [38].

Itaqui – “Clean” Coal power station

The Itaqui fossil fuel power plant is a 360 MW capacity coal fired power station being constructed by MPX Energy in São Luis in the state of Maranhão (NE region). The project has a total investment of $891 million, of which 30% will be allocated to environmental control technologies to enable “clean” coal burning [38]. MPX have not explicitly stated that this “clean” coal power station will have carbon collection and sequestration (CCS), however, the LCOE analysis (sections 6 - 9) assumes the plant will incorporate CCS and reduce its CO_2 emissions by 90%. The capacity factor of the Itaqui plant was assumed to be the same as that for the Energia Pecém coal power station.

Açu II - Gas power station

The Açu II fossil fuel power plant is a 3300 MW capacity gas fired power station being constructed by MPX Energy in the municipality of São João da Barra 300km from Rio de Janeiro. The project has a total estimated investment of $2 billion and will use combined cycle technology, combining gas turbine, heat recovery boiler and steam turbine [38].

Parnaíba - Gas power station

The Parnaíba fossil fuel power plant is a 3722 MW capacity gas fired power station being constructed by MPX Energy in the municipality of Santo Antônio dos Lopes 300km from São Luis in the state of Maranhão (NE region). The project has a total investment of $1.5 billion and will feature 19 GE turbines each with a nominal rating of 183 MW [38]. A capacity factor of 80% was assumed for both gas fired power stations.

Other technologies

Currently there are no examples of commercial scale wave power plants or concentrated solar thermal power (CSP) installations operating in Brazil. Therefore, additional LCOE data from international studies [5, 21] for wave power and CSP technologies was considered in the overall analysis.

5. FINANCIAL AND TECHNICAL INFORMATION COLLECTED

Input data including total investment, O & M, and fuel costs together with installed power specifications, annual energy generation, capacity factor data, construction lead times and assumed lifetime for all the case studies is summarised in table 2. (An exchange rate of US$1 = R$2.02 (from May 2013) was used to convert Brazilian Reais to US dollars).

Table 2: Case study input data.

Project input data	Units	Brotas de Macaúbas Wind	Caetité, Guanambi & Igaporã Wind	Belo Monte Hydro	Santo Antônio Hydro	BEN Biomass	Angra 3 Nuclear	Itaqui CLEAN Coal	Energia Pecém Coal	Açu II Gas	Parnaíba Gas	Tauá Solar	Pituaçu Solar	Bom Jesus da Lapa CSP
Installed Capacity	MW	90	294	11,233	3,150	53	1,405	360	720	3,300	*3,722*	1.0	0.408	30
Capacity Factor	**%**	**40%**	**46%**	**40%**	**70%**	***85%***	**81%**	***85%***	**85%**	***80%***	***80%***	**18%**	**18%**	***20%***
Average Power Generated	MW	35.7	134.0	4,462	2,218	45.1	1,142	306	615	2,640	2,978	0.178	0.072	6
Hours per year	hrs/year	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760
Energy Generated per year	**MWh/yr**	**312,732**	**1,173,840**	**39,087,120**	**19,429,680**	**394,638**	**10,000,000**	**2,680,560**	**5,387,400**	**23,126,400**	**26,083,776**	**1,560**	**630**	**52,560**
Wholesale price of energy	$/MWh	68.81	72.25	39.09	38.61	no data	73.59	no data	no data	*61.88*	61.88	no data	*creditted*	no data
Investiment Cost	**$ millions**	**193**	**579**	**14,851**	**7,475**	**92**	**5,149**	**891**	**1,386**	**1,980**	**1,485**	**5.0**	**2.3**	**131**
Costs per kW of installed capacity	$/kW(inst)	2,141	1,973	1,322	2,373	1,728	3,664	2,475	1,925	600	399	4,950	5,581	4,370
Cost per kWaverage generated	$/kW(ave)	5,398	4,322	3,328	3,370	2,033	4,510	2,912	2,254	750	499	27,799	31,664	21,850
Operation & Maintenance (NEA, 2010)	**$/MWh**	1% of investment	1% of investment	**2.20**	**2.20**	**28.53**	**14.08**	**34.3 / 39.8**	**34.3 / 39.8**	**4.89**	**4.89**	0.25% of investment	0.25% of investment	**42.95**
Decommissioning (NEA, 2010)	$/MWh	**≈ 0**	**≈ 0**	**≈ 0**	**≈ 0**	**≈ 0**	**0.76**	**≈ 0**	**≈ 0**	**≈ 0**	**≈ 0**	**≈ 0**	**≈ 0**	**≈ 0**
Price of Fuel (NEA, 2010)	**$/MWh**	N/A	N/A	N/A	N/A	**17.33**	**10.55**	**13.94**	**13.94**	**52.35**	**52.35**	N/A	N/A	N/A
Emissions factor (CO2 Credits/MWh)	tCO2eq/MWh	**0.2055**	0.2055			**0.2055**						**0.2055**	0.2055	**0.2055**
CO2eq emissions (SRREN, 2012)	kgCO2eq/MWh	12	12	**287**	33	37	16	**100**	**1,001**	**469**	**469**	46	46	22
CO2eq emissions(+) / credits(-) per year	tCOeq/yr	-64,266	-241,224	11,200,000	641,179	-81,098	160,000	268,324	5,392,787	10,846,282	12,233,291	-321	-129	-10,801
Lead construction times (NEA, 2010)	years	**1**	**1**	**4 through 8**	**4 though 7**	**2**	**6**	**4**	**4**	**2**	**2**	**1**	**1**	**1**
Assumed Lifetime of technology	**years**	**35**	**35**	**60**	**60**	**40**	**50**	**40**	**40**	**30**	**30**	**30**	**30**	**30**

Explanations and assumptions:

Published investment costs for each project were considered to be the overnight capital investment cost of the said project.

O & M costs, Decommissioning costs and Price of Fuel data for the hydroelectric, biomass, nuclear, coal and gas power plants in Brazil were taken from the NEA-IEA-OECD “Projected Costs of Generating Electricity” [5]. With the exception of the nuclear plant, due to the levelised cost methodology, decommissioning costs become almost negligible once discounted over the assumed lifetime of a plant. According to the NEA-IEA-OECD report [5] for fossil fuel plants, the residual value of equipment and materials is often assumed to be equal to the cost of decommissioning and the scrap value of the renewable installation is estimated to amount to 20% of the original capital investment.

O & M costs for the Brotas de Macaúbas wind farm were approximately 1% of the total investment [35]. Therefore, the O & M costs for the Caetité, Guanambi and Igaporã wind farm complex were assumed to be 1% of the total investment for that project.

Taxes were not included in the LCOE calculations.

When available, published capacity factors were used. Capacity factors shown in italic text were estimated according to the type of generation technology.

The CO$_{2eq}$ emissions intensity (CO$_{2eq}$/MWh) for the Belo Monte and Babaquara dams was estimated according to Fearnside [33].

For the Itaqui “Clean” coal plant it was assumed the CCS system would reduce emissions of CO$_2$/MWh by 90% compared to a normal coal plant.

Lead construction times for the hydroelectric and nuclear plants were taken from publicly available information. For all the other technologies, lead construction times from the NEA-IEA-OECD “Projected Costs of Generating Electricity” [5] report were used.

Exchange rates: For Brazilian data taken from the NEA-IEA-OECD report [5], a rate of US$1 = R$1.83 was used to convert US dollars to Reais as this was the original exchange rate used in the report. Then a rate of US$1 = R$2.02 (for May 2013) was used to convert back to US dollars.

6. INITIAL LCOE RESULTS

6.1. Low discount rate scenario without social, environmental and transmission externalities

From all the data collected the LCOE was calculated using the real interest rate of 5% for all the Brazilian case studies considered and also for the international examples of CSP and wave power technologies. Figure 3, shows the LCOE separated by component costs for all the Brazilian case studies (with the exception of the solar power projects).

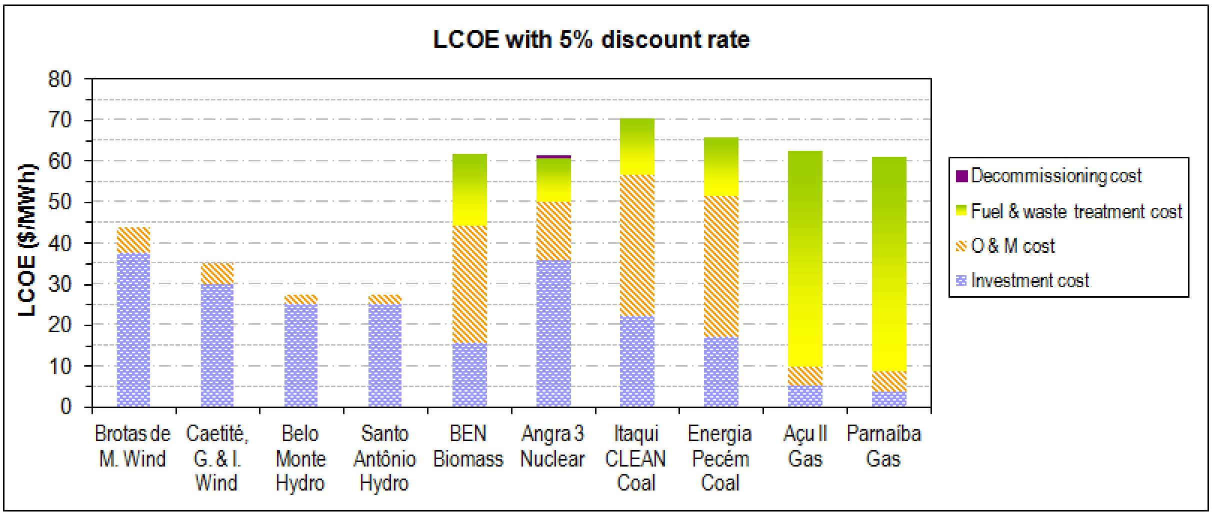


Figure 3: LCOE with low discount rate scenario.

Figure 4, shows the LCOE separated by component costs for the Brazilian PV and CSP case studies, and for the international CSP and wave power projects.

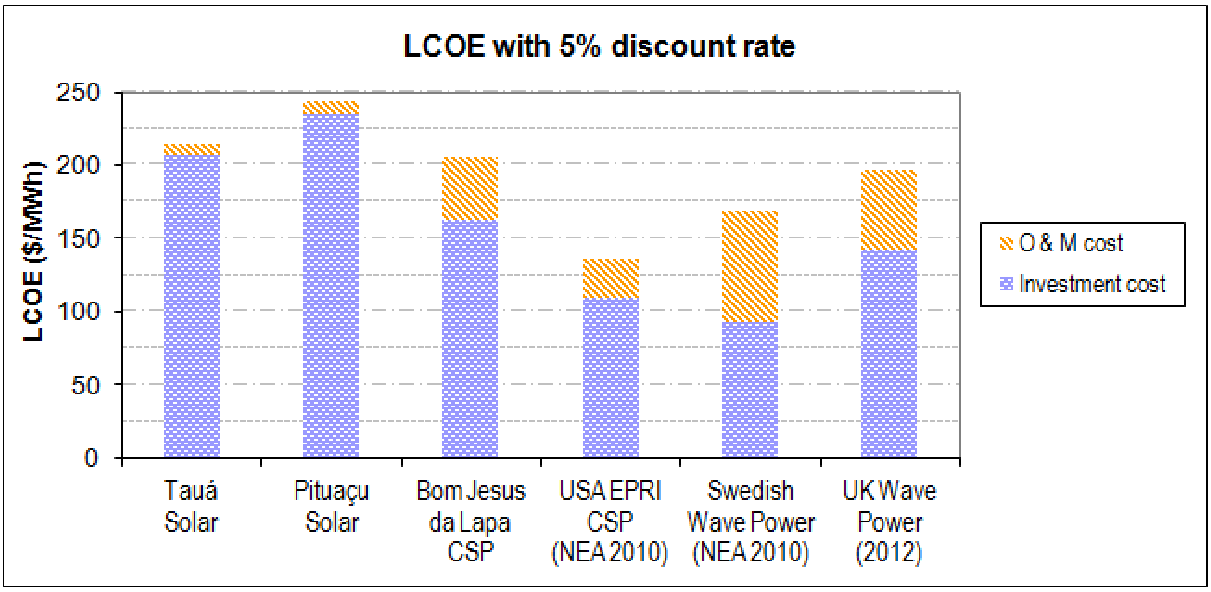


Figure 4: LCOE with low discount rate scenario.

First, considering the results using a 5% discount rate without social, environmental and transmission costs, the LCOE analysis shows that the cheapest technology of all the case studies analysed was hydroelectricity. Both plants have a LCOE of approximately $27.50/MWh.

Wind power is the second cheapest generation technology in Brazil. The Caetité, Guanambi and Igaporã wind farm complex, has a LCOE of $35/MWh and Brotas de Macaúbas Wind Farm has a net LCOE of $41.67/MWh (considering that currently this project receives a carbon credit of R$4.17/MWh). Despite the fact that Brotas de Macaúbas benefits from carbon credits it was still more expensive than the other wind farms due to a lower capacity factor and a more expensive overnight cost per MW of installed capacity.

The biomass, fossil fuel and nuclear technologies all have a LCOE ranging from approximately $61/MWh for the Parnaíba gas plant and the nuclear reactor, to $70.70/MWh for the Itaqui – “Clean” Coal power station. The “clean” coal power station was more expensive than the Pecém plant due to the 30% increase in capital costs for the emissions control and CCS technologies.

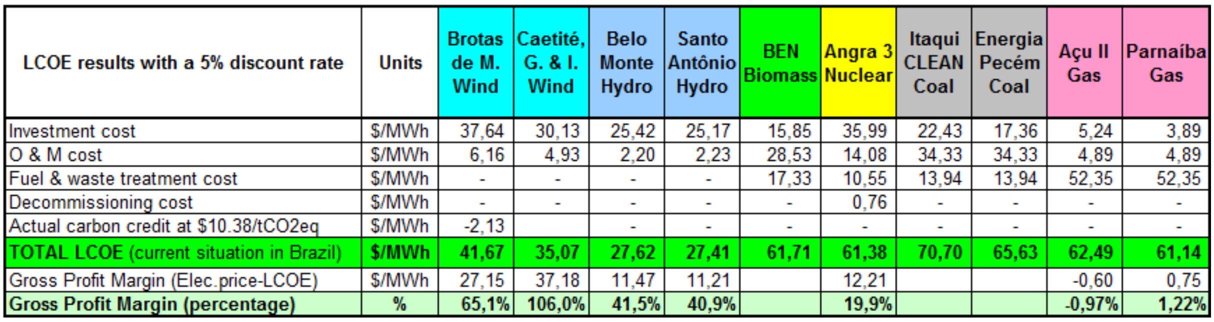
Considering PV, CSP and wave power technologies analysed, the USA EPRI CSP plant with a LCOE of $136/MWh was the cheapest and not surprisingly was significantly cheaper than the Brazilian solar thermal case study. (In fact, of all the solar thermal projects analysed in the

NEA-IEA-OECD [5] report, the USA EPRI CSP plant was cheapest and had the highest capacity factor of 34%). The second cheapest of these developing renewable technologies (CSP and wave power) was the Swedish wave power plant with a LCOE of $169/MWh and a capacity factor of 35%. In fact it was the cheapest of all wave power projects analysed in the NEA-IEA-OECD [5] report. Though not considered in the above comparison it is worth mentioning that the Australian wave power plant was only marginally more expensive than the Swedish plant, with a LCOE of $172/MWh, but has a far better capacity factor of 56% [5]. Given the power and consistency of ocean waves and tidal movement, wave and tidal generators have an advantage of greater output regularity and higher capacity factors compared to wind and solar power. Ricarte and Estefen [45] compares the cost of generating electricity from wave, wind, hydro, solar and thermal power, and claim that, at utility scale, wave energy theoretically has the potential to be at least 30% cheaper than wind power and equivalent to or marginally cheaper than hydro.

The Brazilian solar power case studies all have a LCOE above $205/MWh making them uncompetitive compared to the other technologies. The Solar PV systems with LCOE results of $214/MWh and $244/MWh for the Tauá and Pituaçu solar systems, respectively, were the most expensive technologies, however, that does not necessarily mean that PV technology is economically unviable in Brazil. The new ANEEL regulations implemented at the end of 2012 allow PV systems to be installed at a property and connected to the electricity grid. Furthermore, any excess PV generated electricity not used by the premises will be bought back by the electricity utility company in the form of credits. The Pituaçu stadium incurs a relatively low (public/municipal) electricity tariff of $210/MWh, and therefore without government subsidies, the Pituaçu PV system would still incur an overall loss compared to the cost of the grid electricity. However, it is worth noting that commercial and residential tariffs in Bahia are $295/MWh and $287/MWh, respectively [46]. Given these tariffs are significantly higher than the LCOE (at a 5% discount rate) for both PV projects, grid connected PV systems at suitable commercial and residential locations would be economically viable. Locations considered suitable are those that receive good levels of solar radiation throughout the day and where installation costs can be kept to a minimum. Most large warehouses, shopping centres, government buildings and high-rise buildings in the Northeast of Brazil would fit into this category [47]. The gross profit margin for PV installations at commercial premises would be in the order of $80/MWh or 37%, considering the LCOE for the Tauá solar PV system as a benchmark.

The gross profit margin for some of the other case studies was calculated by comparing the LCOE for a particular case study to its specific wholesale price of electricity (agreed in the national energy auctions for contracting electricity generation projects). The gross profit margins, for those case study projects where wholesale energy price data was available, are shown in table 3.

Table 3: LCOE and gross profit margin for large-scale case studies using a real discount rate of 5%.



LCOE results with a 5% discount rate	**Units**	**Brotas de M. Wind**	**Caetité, G. & I. Wind**	**Belo Monte Hydro**	**Santo Antônio Hydro**	**BEN Biomass**	**Angra 3 Nuclear**	**Itaqui CLEAN Coal**	**Energia Pecém Coal**	**Açu II Gas**	**Parnaíba Gas**
Investment cost	$/MWh	37,64	30,13	25,42	25,17	15,85	35,99	22,43	17,36	5,24	3,89
O & M cost	$/MWh	6,16	4,93	2,20	2,23	28,53	14,08	34,33	34,33	4,89	4,89
Fuel & waste treatment cost	$/MWh	-	-	-	-	17,33	10,55	13,94	13,94	52,35	52,35
Decommissioning cost	$/MWh	-	-	-	-	-	0,76	-	-	-	-
Actual carbon credit at $10.38/tCO2eq	$/MWh	-2,13		-	-	-	-	-	-	-	-
TOTAL LCOE (current situation in Brazil)	**$/MWh**	**41,67**	**35,07**	**27,62**	**27,41**	**61,71**	**61,38**	**70,70**	**65,63**	**62,49**	**61,14**
Gross Profit Margin (Elec.price-LCOE)	$/MWh	27,15	37,18	11,47	11,21		12,21			-0,60	0,75
Gross Profit Margin (percentage)	**%**	**65,1%**	**106,0%**	**41,5%**	**40,9%**		**19,9%**			**-0,97%**	**1,22%**

7. SENSITIVITY ANALYSIS

By analysing the LCOE of various generation technologies with a real discount rate of both 5% and 10%, it can be observed that the LCOE for those technologies with long lead times (such as nuclear power) and with a higher proportion of capital investment (such as the renewable technologies) are more susceptible to variations in the discount rate. For example, nuclear, PV, wind power and hydroelectricity become significantly more expensive when using the higher discount rate. On the other hand electricity generated from those technologies which have a significant proportion of operational costs (such as biomass, coal power or gas turbine electricity) are far less susceptible to changes in the discount rate, because these technologies have smaller capital costs. Figure 5, shows the LCOE with a real discount rate of 10% separated by component costs for all the Brazilian case studies (with the exception of the solar power projects).

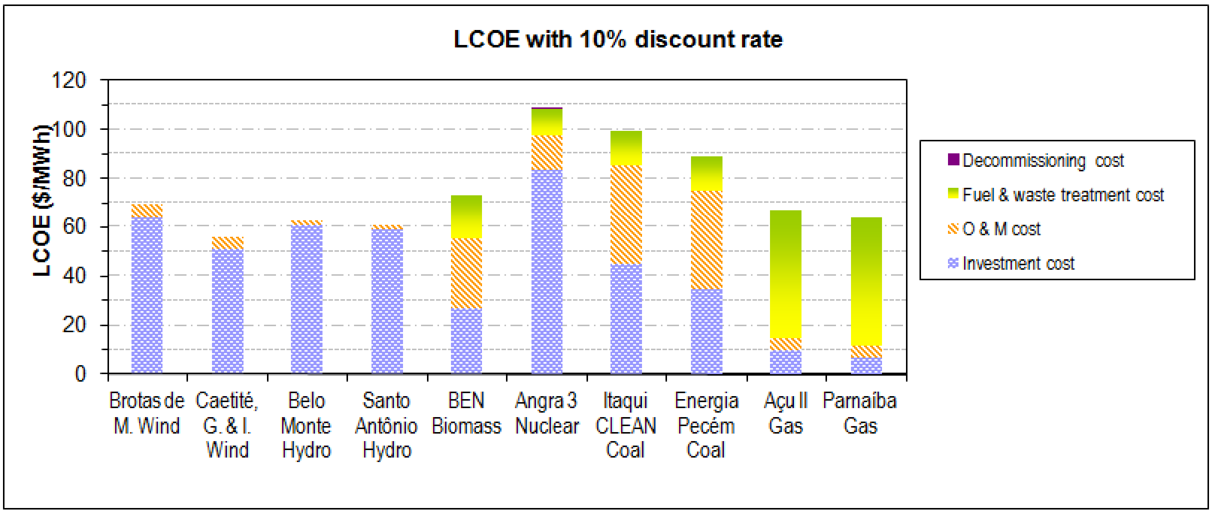


Figure 5: LCOE with high discount rate scenario.

By using the real discount rate, the real LCOE of a plant (during its entire lifecycle) can be expressed in real $/MWh which removes the impact of inflation. The assumption is that inflation and the discount rate remain constant throughout the life of the project. However, if fuel and/or O & M costs increase above the rate of inflation (during the life of the project) this will impact more on the LCOE of those generation technologies most dependent on fuel and/or O & M. For example, if there is a sharp increase in the price of fossil fuel, then the cost of electricity from gas and oil power plants in particular (and also coal power plants) would increase significantly more than the LCOE from other generation technologies. On the other hand, if the price of gas drops then the LCOE for gas power plants would drop proportionally.

Similarly, if O & M costs increase significantly above the standard inflation rate, the cost of electricity from the coal and biomass power plants would increase significantly more than the costs of electricity from other generation technologies. Additionally the LCOE from fossil fuel plants are susceptible to increases in a future carbon tax if implemented. Thus for all the above reasons, traditional generation technologies, such as gas, oil and coal fuelled plants, have greater financial risks due to the possibility that plant running costs could rise in the future.

On the other hand, it can be concluded that the lifecycle costs of renewable technologies are far less susceptible to the predicted increases in future fossil fuel prices and carbon taxes, and are also less susceptible to variations in labour and maintenance costs.

8. SOCIAL, ENVIRONMENTAL AND TRANSMISSION EXTERNALITIES

8.1. Social and environmental impacts of large hydroelectric plants in the Amazon

A major criticism of the Belo Monte plant is that it will generate only about 10% of its full capacity during the three to four months of dry season each year. The only way for the Belo Monte project to generate close to 100% of its full capacity year round and thus be more economically viable, is if the much larger proposed Babaquara dam is built at some point in the future. However, because of its very large size, this dam may not be granted an environmental licence for many years to come.

Large hydroelectric dams such as Belo Monte are planned for the Amazon region; however, such dams in the Amazon basin will cause significant environmental conflicts. It is predicted that the Belo Monte dam and the much larger Babaquara dam upstream with a reservoir area of 6140 km^2 (if finally completed) will emit at least 11.2 million tonnes of carbon dioxide equivalent emissions per year for the first 10 years via methane gas and CO_2 which will be produced by decomposing forest and foliage in the flooded reservoirs [33]. These CO_2 equivalent emissions estimates are subject to a degree of uncertainty and after the first 10 years the annual emissions from the reservoirs are predicted to slowly decline. Fearnside [33] also claims the emissions during the first 10 years could be as much as 4 times the emissions from an equivalent sized fossil fuel gas plant. This figure may be an overestimate; nevertheless there is significant scientific evidence that large hydroelectric dams in the Amazon do produce substantial greenhouse gas emissions. Using the methodology of Alves and Uturbey [32] the Belo Monte and Babaquara dam (if built) would produce almost 14 million tonnes of carbon dioxide equivalent emissions per year for the first 10 years.[7] However, it is worth noting that if the Babaquara dam is never built, then the Belo Monte dam alone will only produce approximately 1 million tonnes of carbon dioxide equivalent emissions per year for the first 10 years.

As a result of the construction of the Belo Monte dam several thousand people will have to be relocated. Furthermore, rather than with a goal for the generated electricity to benefit communities in the region, approximately 30% of the electricity will be used for the

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[7] In comparison, the Santo Antônio dam will only produce approximately 0.6 million tonnes of carbon dioxide equivalent emissions per year for the first 10 years, because its reservoir is almost 25 times smaller.

extraction of large mineral deposits in Pará, including the processing of bauxite and aluminium oxide [33]. Such environmental and social costs will have significant negative impacts in the coming years. However, they are not easily measured quantitatively and are generally not included in economic viability calculations or planning decisions. Therefore, as well as considering the typical economic indicators of different generation technologies, it is important to also consider the environmental impacts and estimate their financial cost.

8.2. Social and environmental externality costs

Social and environmental externalities (such as greenhouse gas damage, acid rain, and particulate emissions) caused by coal and gas fired power-stations have negative impacts on climate, human health, crops, structures and biodiversity. The conclusion of the extensive ExternE study [29, 30] for Europe arrived at total external costs for black coal of €41/MWh (€17/MWh due to health damage impacts and €24/MWh due to greenhouse gas (GHG) emission). The health damage cost actually makes up 50% of the operational externalities of coal plants due to their particulate, SO_2 and NO_x emissions. As well impacting on human health and crop yield, SO_2 causes acid rain, and NO_x contributes to the breakdown of the nitrogen cycle (via eutrophication). For gas turbine plants the total external costs were estimated at €16/MWh (€2.5/MWh due to health damage impacts and €13.5/MWh due to greenhouse gas emission) [31], while combined cycle plants had slightly lower externality costs. Assuming that these studies can loosely be applied to Brazil (using an exchange rate of \$1 = €0.77 from May 2013), the total externality costs due to health impacts and GHG emissions from black coal without CCS and gas electricity generation in Brazil amount to approximately \$53/MWh and \$21/MWh, respectively.

In comparison, the total externality costs due to wind power and solar (thermal or PV) were estimated to be €0.90/MWh (\$1.17/MWh) and approximately €3/MWh (\$3.90/MWh), respectively [30, 31]. These ExternE estimates were based on a European energy mix for the manufacturing of wind turbine and solar power equipment. If however, the majority of the equipment for these technologies is manufactured in Brazil, where currently the electricity matrix has a very low CO_{2eq} emissions factor, these estimates could be reduced by at least 50-75%. The majority of wind turbines installed in Brazil are manufactured locally, hence it can be concluded that the externality costs due to wind power in Brazil are almost negligible.

Similarly, the ExternE result for the total externality costs from nuclear power was €4.20/MWh or $5.45/MWh [30, 31]. Also, compared to other technologies, the ExternE project had a very wide range of values for nuclear power externalities of €0.6/MWh to €7/MWh. These valuations do not consider the costs of the low probability / risk of severe reactor accidents. The ExternE study stated that there was no accepted method to calculate risk aversion for *“beyond-design accidents”* as *“their monetary valuation cannot be readily determined”* [31]. Additionally, Diesendorf [48] states that CO_{2eq} emissions intensity from the nuclear energy life cycle considering low grade uranium ore and the rehabilitation of mine waste would be equivalent to that of a gas power plant. He also argues that the risk of nuclear accidents and proliferation, as well as the lack of long-term high grade ore and secure repositories for radioactive waste, render nuclear power environmentally and commercially unsustainable [48]. Therefore the actual environmental externalities of nuclear power could greatly exceed the ExternE estimates.

The impact due to GHG emissions will have global effects. Yet, it is worth noting that in all likelihood tropical countries and in particular the semi-arid region of the NE of Brazil will be more severely affected by climate change and extreme weather events caused by GHG emissions than other regions [8]. Moreover, climate change is predicted to increase the severity of long droughts which can reduce the output from hydroelectric plants [47, 49-50]. Since 2012, the NE region has been suffering from one of its worst droughts in decades. As a result, hydroelectricity generation in 2014 was 36% below its mean output during non-drought years [10].

The GHG damage cost for the Belo Monte and Babaquara dams can be easily estimated. Using the ExternE [31] GHG impact cost figure for coal power plants of €24/MWh, the total GHG impact cost per tonne of CO_2 can be derived as €24/tCO_{2eq}. Then using this derived figure, the greenhouse gas damage caused by the Belo Monte dams during the first 10 years is estimated to be €7.19/MWh (or $9.33/MWh). (Note that by using the Alves and Uturbey [32] methodology, a similar figure of $9.22/MWh was arrived at). If this externality cost is taken into consideration, the LCOE for Belo Monte would then increase to above $36.94/MWh (at the 5% discount rate) making it more expensive than the cheaper wind farm project. It should also be noted that this calculation assumes that there are no other environmental externalities and also negligible health damage and social impact costs from the Belo Monte project, though in reality these will be quite substantial. According to the Brazilian Ministry of Mines and Energy [42], approximately 16% of the total investment for the Belo Monte hydroelectric plant will be put to social and environmental programs. This is equivalent to \$4.07/MWh at the 5% discount rate and \$9.73/MWh at the 10% discount rate for social and environmental expenses. However, these values are already included within the investment component of the LCOE for Belo Monte.

Although not the focus of this study, biomass energy production for ethanol fuel and electricity generation can also impact the environment as it can cause conflict in the use of soil, land and water. If semi-arid or unfertile land is used for biomass production without the need to supplement rain water with irrigation water, then the impacts on the environment are restricted to the health cost externalities caused by particulate matter and NO_x emissions from the plant smokestack. Using the ExternE [30, 31] results, the average externality costs for biomass were estimated to be €11.64/MWh or \$15.11/MWh. However, on the positive side, the ethanol and electricity produced from biomass will displace the need to produce energy from fossil fuels. If, however, biomass production results in large amounts of water and/or fertilizer consumption, the clearing of forests, or uses fertile land which would otherwise have been used for food production, then the additional environmental and social impacts would be quite considerable [47, 51].

As a result of the growing electricity deficit in the NE, a number of large fossil fuel power plants are already under construction in the region (the Parnaíba gas power plant and coal power plant case studies are prime examples) and more are planned. Therefore, though these plants are not currently subject to carbon taxes, the GHG and air pollution they produce will cause social and environmental externality costs as mentioned above and these costs will indirectly increase the LCOE of these fossil fuel plants. Currently, the community, farmers and the government will indirectly foot the “externality” bill of \$53/MWh, \$21/MWh and \$9.33/MWh for damage caused by emissions from coal power plants, gas power plants and Belo Monte, respectively (at 2005 prices). This result suggests that for these externalities to be internalised, a carbon tax of approximately \$50-\$55/tCO_{2eq} would be needed. Moreover, this is a conservative estimate, as it does not account for inflation since 2005.

8.3. Transmission system externality costs

At significant cost, Belo Monte, when completed will partly resolve power shortages in Brazil for a number of years. It will also increase energy imported from the Brazilian North to the NE and Southeast regions, but with a corresponding increase in power losses due to the extraordinary length of transmission lines required to transmit the electricity to the NE and the Southeast regions. The Santo Antônio hydroelectric plant, due to its extreme remoteness, will also have a very extensive transmission line. With a length of 2400 km and a DC voltage of 600kV, [43] claim it will be one of the largest electrical transmission systems in the world. The massive costs of these transmission lines and resulting energy losses are not generally included in LCOE calculations.

Based on the Delucchi and Jacobson [34] results for the losses and costs of extra-long transmission systems, a figure of $300/MW-km was used to calculate the capital cost of such transmission lines in Brazil. Assuming that the Santo Antônio transmission system will have an approximate capacity of 3150MW (the same as the plant capacity), its total investment was estimated to be almost $2.3 billion. (This is comparable to published data of $5 billion for the Madeira transmission system [52], which will serve both the Santo Antônio and Jirau hydroelectric plants if one considers that the Santo Antônio plant makes up 46% of the installed capacity of both the hydroelectric plants together). Therefore, the transmission system's total cost per MWh was calculated to be $8.47/MWh at the 5% discount rate and $19.83/MWh at the 10% discount rate. The total energy loss, due to the Santo Antônio transmission system, was estimated to be 9.8%, which means that only 90.2% of the total energy generated at the hydroelectric plant is supplied to the distribution network. As a result, the actual LCOE delivered to the distribution network by the Santo Antônio hydroelectric plant increases proportionally.

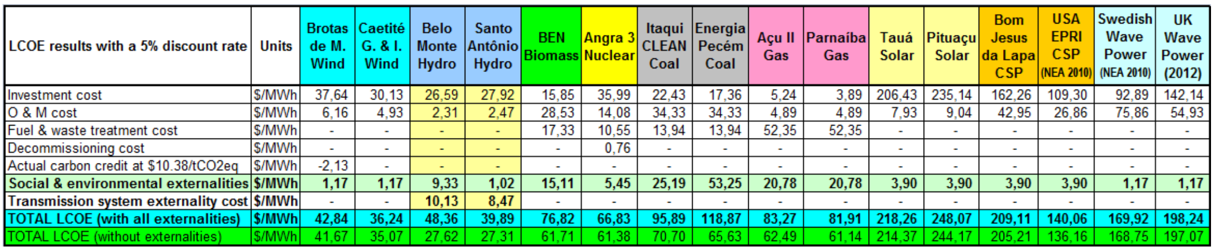
Two new 800kV DC transmission systems of 2140km and 2575km, each with a capacity of 4000MW, are being constructed to deliver power from Belo Monte to the Southeast of Brazil [53, 54]. Using the Delucchi and Jacobson [34] results above, the energy losses at full capacity for these transmission lines would be 6.0% and 7.2%, respectively. Due to Belo Monte's enormous capacity, it is assumed that approximately 2/3 of energy it produces will supply the Southeast via these two transmission systems. However, as Belo Monte is relatively near some large load centres in the North and Northeast regions, it is also assumed that 1/3 of the energy it produces will supply these areas without significant losses. Therefore, the overall power losses due to the transmission systems would be 4.4% or 494MW at full capacity. Using the figure of $300/MW-km, the total investment for both transmission systems was estimated to be almost $ 5.7 billion. The total cost per MWh of both transmission systems was calculated to be $10.13/MWh at the 5% discount rate and $24.23/MWh at the 10% discount rate. As above, the actual LCOE delivered to the distribution network by the Belo Monte hydroelectric plant was adjusted to incorporate the 4.4% of transmission system energy losses.

In contrast to the large hydroelectric plants in the Amazon, all the other case study projects are located much nearer electricity load centres and thus have transmission lines of 0-300km in length. Consequently, it can be reasonably assumed that the losses and cost per MWh of their transmission lines are insignificant. The transmission line of the Tauá solar PV plant is only 12km long. The Caetité, Igaporã and Guanambi wind farm complex has 77km of transmission lines. One advantage of the roof mounted Pituaçu Solar PV system is that it is connected directly to the distribution network. Distributed PV and also roof mounted wind turbines have the advantage that they don’t require transmission lines and land usage is not an issue.

9. AGGREGATE LCOE RESULTS

The overall LCOE for all the case studies including their respective environmental externality and transmission system costs is shown in tables 4 and 5 and figures 6 and 7. The impact of the respective transmission system costs and losses to the total LCOE for both hydroelectric plants can also be observed.

Table 4: LCOE for all the case studies, using a real discount rate of 5%, with social, environmental and transmission system externality costs.



LCOE results with a 5% discount rate	Units	Brotas de M. Wind	Caetité G. & I. Wind	Belo Monte Hydro	Santo Antônio Hydro	BEN Biomass	Angra 3 Nuclear	Itaqui CLEAN Coal	Energia Pecém Coal	Açu II Gas	Parnaíba Gas	Tauá Solar	Pituaçu Solar	Bom Jesus da Lapa CSP	USA EPRI CSP (NEA 2010)	Swedish Wave Power (NEA 2010)	UK Wave Power (2012)
Investment cost	$/MWh	37,64	30,13	26,59	27,92	15,85	35,99	22,43	17,36	5,24	3,89	206,43	235,14	162,26	109,30	92,89	142,14
O & M cost	$/MWh	6,16	4,93	2,31	2,47	28,53	14,08	34,33	34,33	4,89	4,89	7,93	9,04	42,95	26,86	75,86	54,93
Fuel & waste treatment cost	$/MWh	-	-	-	-	17,33	10,55	13,94	13,94	52,35	52,35	-	-	-	-	-	-
Decommissioning cost	$/MWh	-	-	-	-	-	0,76	-	-	-	-	-	-	-	-	-	-
Actual carbon credit at $10.38/tCO2eq	$/MWh	-2,13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Social & environmental externalities	**$/MWh**	**1,17**	**1,17**	**9,33**	**1,02**	**15,11**	**5,45**	**25,19**	**53,25**	**20,78**	**20,78**	**3,90**	**3,90**	**3,90**	**3,90**	**1,17**	**1,17**
Transmission system externality cost	**$/MWh**	-	-	**10,13**	**8,47**	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL LCOE (with all externalities)	**$/MWh**	**42,84**	**36,24**	**48,36**	**39,89**	**76,82**	**66,83**	**95,89**	**118,87**	**83,27**	**81,91**	**218,26**	**248,07**	**209,11**	**140,06**	**169,92**	**198,24**
TOTAL LCOE (without externalities)	$/MWh	41,67	35,07	27,62	27,31	61,71	61,38	70,70	65,63	62,49	61,14	214,37	244,17	205,21	136,16	168,75	197,07

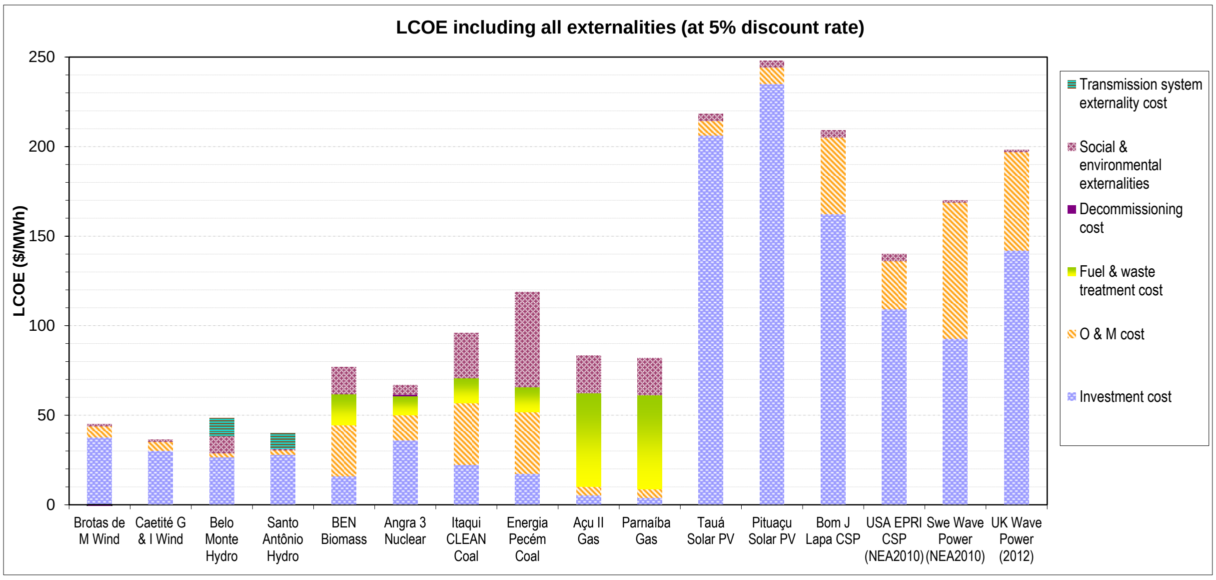


Figure 6: LCOE shown graphically at a 5% discount rate with social, environmental and transmission system externality costs.

Table 5: LCOE for all the case studies, using a real discount rate of 10%, with social, environmental and transmission system externality costs.

LCOE results with a 10% discount rate	Units	Brotas de M. Wind	Caetité G. & I. Wind	Belo Monte Hydro	Santo Antônio Hydro	BEN Biomass	Angra 3 Nuclear	Itaqui CLEAN Coal	Energia Pecém Coal	Açu II Gas	Parnaíba Gas	Tauá Solar	Pituaçu Solar	Bom Jesus da Lapa CSP	USA EPRI CSP (NEA 2010)	Swedish Wave Power (NEA 2010)	UK Wave Power (2012)
Investment cost	$/MWh	63,90	51,16	63,60	65,34	27,08	83,63	45,25	35,02	9,63	6,64	336,63	383,44	264,59	175,59	148,29	237,10
O & M cost	$/MWh	5,83	4,93	2,31	2,47	28,53	14,08	39,80	39,80	4,89	4,89	7,93	9,04	42,95	26,86	75,86	54,93
Fuel & waste treatment cost	$/MWh	-	-	-	-	17,33	10,55	13,94	13,94	52,35	52,35	-	-	-	-	-	-
Decommissioning cost	$/MWh	-	-	-	-	-	0,76	-	-	-	-	-	-	-	-	-	-
Actual carbon credit at $10.38/tCO2eq	$/MWh	-2,13	-	-	-	-	-	-	-	-	-	-	-	-	-		-
Social & environmental externalities	**$/MWh**	**1,17**	**1,17**	**9,33**	**1,02**	**15,11**	**5,45**	**25,19**	**53,25**	**20,78**	**20,78**	**3,90**	**3,90**	**3,90**	**3,90**	**1,17**	**1,17**
Transmission system externality cost	**$/MWh**	-	-	**24,23**	**19,83**	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL LCOE (with all externalities)	**$/MWh**	**68,77**	**57,27**	**99,47**	**88,66**	**88,05**	**114,47**	**124,18**	**142,01**	**87,66**	**84,67**	**348,46**	**396,37**	**311,44**	**206,35**	**225,32**	**293,20**
TOTAL LCOE (without externalities)	$/MWh	67,60	56,10	63,01	61,14	72,94	109,01	93,51	83,29	66,88	63,89	344,56	392,48	307,55	202,45	224,15	292,03

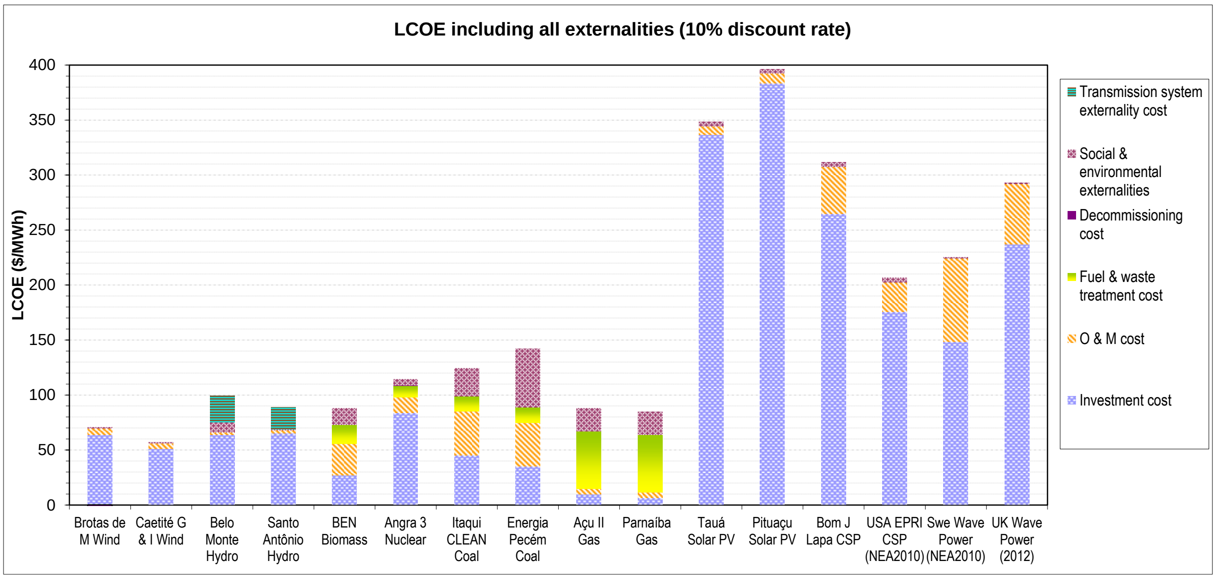


Figure 7: LCOE shown graphically at a 10% discount rate with social, environmental and transmission system externality costs.

With the 5% discount rate it can be observed that once all externalities are taken into consideration, the wind farm case studies become more competitive than Belo Monte and as competitive as Santo Antônio. The coal and gas power plants become uncompetitive in comparison. It should also be noted that the coal plant without CCS is only 15% cheaper than the USA CSP plant. With the 10% discount rate, the wind farm case studies become at least 22% and 31% cheaper than the Santo Antônio and Belo Monte hydroelectric plants, respectively, and also significantly more competitive than all the other case studies analysed.

Apart from new hydroelectric plants in the Amazon and new fossil fuel plants which both have very large externality costs, new wind farms, such as Brotas de Macaúbas, are being constructed in the Northeast region and several more have been approved. Fortunately, due to strong wind regimes in the dry season, these wind farms will produce the majority of their output during the period when hydroelectric potential is at its lowest level. Solar irradiation is also strong at the end of the dry season when reservoir levels are low [55]. The complementarity of wind power and solar energy with the existing hydroelectric infrastructure helps diversify electricity generation and improves energy security in Brazil [3, 47]. Wind power can compensate for lost hydroelectric availability during drought periods, while hydroelectric plants have ample dynamic response and storage capabilities to counterbalance the intermittence of wind power [50, 56-58]. This complementarity combined with the minimal environmental impact of wind and solar energy, are big added values for these renewable technologies that cannot easily be given a financial value.

10. CONCLUSION

Considering the current situation in Brazil (using a 5% discount rate) results, not considering externalities, showed that the hydroelectric plants had the lowest LCOE due to their large economies of scales, but were only slightly cheaper than the wind power case studies. Additionally, when using a 10% discount rate, the Caetité, Guanambi and Igaporã wind power case study actually had the lowest LCOE of all the case studies.

Solar photovoltaic (PV) was found to be the most expensive technology followed by wave power and concentrated solar thermal power (CSP). Hence, these technologies are unlikely to become competitive without proper government incentives. Nevertheless renewable energy projects would reduce the need for electricity generated by fossil fuel plants and their associated environmental impacts. The majority of Brazil's easily accessible hydroelectric resources are already saturated. Consequently, unless proper incentives are provided for solar, wind, geothermal and wave energy development, the national emissions factor is likely to increase with the construction of new fossil fuel plants.

The government is still licensing and over investing in large hydroelectric projects in the Amazon which will have significant environmental impacts and transmission line costs. In contrast, renewable energy sources such as wind and solar power still suffer from unfair barriers that discriminate against renewable energy. The market and decision makers often focus on the high up-front capital costs of renewable energy compared to that of conventional energy sources. A more comprehensive approach would be to focus on the overall LCOE, which includes the lifetime costs of fuel, O & M, transmission systems and environmental impacts of conventional generation technologies.

It was shown that cost estimates of the social and environmental effects of large scale projects can vary significantly. These externalities are rarely shown in the financial evaluations of projects, but will exert enormous costs on the environment, agriculture and society. If all environmental externalities and transmission system (costs and losses) are taken into consideration (at the 5% discount rate) the following conclusions are reached: The LCOE of both wind farm case studies become more competitive than Belo Monte. Furthermore, the Caetité, Guanambi and Igaporã wind farm complex becomes the cheapest of all the case studies. The LCOE of the coal plant with CCS is more than double that of the wind farms. The LCOE of the coal plant without CCS is triple the average LCOE of the wind farms. Considering the cost projections of renewable energy technologies reviewed by Hearps & McConnell [17], CSP and PV will become cheaper than coal power by 2025.

Considering all externalities (transmission system, social and environmental) with the 10% discount rate, both wind farm case studies become significantly more competitive than the hydroelectric plants and have the lowest LCOE among all the case studies analysed. The LCOE of wind power is less than half that of the coal plant (without CCS) and at least 40% cheaper than nuclear power (with the 10% discount rate). In the light of these findings, can the construction of new coal fired power stations and nuclear reactors in Brazil be justified?

To date, government policy has not been effective at promoting solar energy (solar hot-water, CSP and PV). Very recently there has been substantial growth in planned wind farms, however support for solar power lags far behind. To exploit and develop the full potential of wind and solar power in Brazil requires the implementation of effective government policy, more subsidies, tax exemptions and financial incentives to encourage large scale research and deployment. This would close the economic gap that exists between these largely unexploited renewable technologies and traditional generation technologies.

11. ACKNOWLEDGMENT

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12. REFERENCES

[1] Pereira M G, Camacho C F, Freitas M A V, Silva N F. The renewable energy market in Brazil: Current status and potential. Renewable and Sustainable Energy Reviews 2012; 16: 3786–3802.

[2] Bitencourt A F, de Jong P, Torres E A, Andrade J C S. Viabilidade Econômica de Projetos de Energia Eólica, Solar e Hidroelétrica: O Papel dos Créditos de Carbono. ABES – Associação Brasileira de Engenharia Sanitária e Ambiental / AIDIS; 2012.

[3] de Jong P, Sánchez A S, Esquerre K, Kalid R A, Torres E A. Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the Northeast region of Brazil. Renewable and Sustainable Energy Reviews 2013a; 23: 526–535.

[4] ANEEL - Agência Nacional da Energia Elétrica / Brazilian National Electricity Agency, BIG - Banco de Informações de Geração / Information Bank of Generation; 2014. Available at: http://www.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.asp Accessed on 15/03/2015.

[5] NEA-Nuclear Energy Agency/IEA-International Energy Agency/OECD-Organisation for Economic Cooperation and Development. Projected Costs of Generating Electricity; 2010 Edition.

[6] MME - Ministério de Minas e Energia (Brazil), EPE - Empresa de Pesquisa Energética. Balanço Energético Nacional – Ano base 2011; 2012.

[7] Martins F R, Pereira E B. Enhancing information for solar and wind energy technology deployment in Brazil. Energy Policy 2011; 39: 4378–4390.

[8] Tanajura C A S, Genz F, Araujo H. Mudanças climáticas e recursos hídricos na Bahia: validação da simulação do clima presente do HadRM3P e comparação com os cenários A2 e B2 para 2070-2100. Revista Brasileira de Meteorologia ed. online; 2010. vol. 3. p. 345-58.

[9] Pereira de Lucena A F, Szklo A S, Schaeffer R, Dutra R M. The vulnerability of wind power to climate change in Brazil. Renewable Energy 2010; 35: 904-12.

[10] ONS - Operador Nacional do Sistema Elétrico. Históricas da Operação - Geração de Energia; 2015 Available at: http://www.ons.org.br/historico/geracao_energia.aspx Accessed on 12/01/2015.

[11] MME - Ministério de Minas e Energia (Brazil), EPE - Empresa de Pesquisa Energética. Plano Decenal de Expansão de Energia 2020. Brasília: MME/EPE; 2011.

[12] Amarante O A C do, Brower M, Sá A L de, Zack J, Atlas do Potencial Eolico Brasileiro, CRESESB 2001.

[13] NREL - National Renewable Energy Laboratory. 2010 Solar Technologies Market Report. DOE - US Department of Energy; 2011.

[14] Eletrobras – Centrais Elétricas Brasileiras S.A.; PROCEL – Programa Nacional de Conservação de Energia Elétrica. Pesquisa de Posse de Equipamentos e Hábitos de Uso – Ano Base 2005 – Classe Residencial – Relatório Brasil. Rio de Janeiro; 2007.

[15] Silva S B, Oliveira M A G de, Severino M M. Economic evaluation and optimization of a photovoltaic–fuel cell–batteries hybrid system for use in the Brazilian Amazon. Energy Policy 2010; 38: 6713–6723.

[16] ANEEL - Agência Nacional da Energia Elétrica. ANEEL aprova regras para facilitar a geração de energia nas unidades consumidoras; 2012. Available at: http://www.aneel.gov.br/aplicacoes/noticias/Output_Noticias.cfm?Identidade=5457&id_area=90 Accessed on 23/05/2012.

[17] Hearps P, McConnell D. Renewable Energy Technology Cost Review. Melbourne Energy Institute, Technical Paper Series; March 2011.

[18] ATSE. Burgess J M. New Power cost comparisons: Levelised Cost of Electricity for a Range of New Power Generating Technologies. Australian Academy of Technological Sciences and Engineering (ATSE), Melbourne, Victoria, Australia; March 2011.

[19] EIA. Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2014. U.S. Energy Information Administration (EIA); April 2014.

[20] Nicholson M, Biegler T, Brook B W. How carbon pricing changes the relative competitiveness of low-carbon baseload generating technologies. Energy 2011; 36: 305-313.

[21] Allan G, Gilmartin M, Mcgregor P, Swales K. Levelised costs of Wave and Tidal energy in the UK: Cost competitiveness and the importance of ‘‘banded’’ Renewables Obligation Certificates. Energy Policy 2011; 39: 23–39.

[22] Liu G, Rasul M G, Amanullah M T O, Khan M M K. Techno-economic simulation and optimization of residential grid-connected PV system for the Queensland climate. Renewable Energy 2012; 45: 146-155.

[23] APVI - Australian PV Institute. Watt M, Passey R, Noone B, Spooner T. National Survey Report of PV Power Applications in Australia, 2013. APVI, June 2014.

[24] Colle S, Felten B, Abreu S L de. A Monthly Solar Irradiation Based Algorithm To Access the Life Cost Savings of Photovoltaic - Diesel Hybrid Power Plant for Isolated Grids. Proceedings of the ISES Solar World Congress 2009: Renewable Energy Shaping Our Future.

[25] Cardemil J M, Colle S A Base de Dados SWERA Como Suporte para Análises Tecnico-Econòmicas de Plantas Termo-Solares. III Congresso Brasileiro de Energia Solar – Belém; 2010.

[26] IPCC - Intergovernmental Panel on Climate Change. Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN). Cambridge University Press; 2012.

[27] Point Carbon; 2013. Available at: http://www.pointcarbon.com/ Accessed on 22/04/2013.

[28] Stern N. The Economics of Climate Change: The Stern Review. Cambridge, UK: Cambridge University Press, 2007.

[29] ExternE-Pol – Externalities of Energy: Extension of accounting framework and Policy Applications. European Commission, Luxembourg; 2005.

[30] ExternE – Externalities of Energy – Methodology 2005 Update. European Commission, Luxembourg; 2005.

[31] ATSE. The Hidden Costs of Electricity: Externalities of Power Generation in Australia. Australian Academy of Technological Sciences and Engineering (ATSE), Parkville, Victoria, Australia; 2009.

[32] Alves L A, Uturbey W. Environmental degradation costs in electricity generation: The case of the Brazilian electrical matrix Energy Policy 2010; 38: 6204–6214.

[33] Fearnside P M. As hidrelétricas de Belo Monte e Altamira (Babaquara) como fontes de gases de efeito estufa. Novos Cadernos NAEA v. 12, n. 2, p. 5-56, dez. 2009.

[34] Delucchi M A, Jacobson M Z. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. Energy Policy 2011; 39: 1170–1190.

[35] UNFCCC Formulário do Documento de Concepção do Projeto (DCP de MDL), Projeto de MDL das Usinas Eólicas Seabra, Novo Horizonte e Macaúbas; 2010.

[36] Renova Energia. Projetos Eólicos em Operação; 2012. Available at: www.renovaenergia.com.br/pt-br/nossos-negocios/eolica/Paginas/default.aspx Accessed on 04/07/2012.

[37] MPX Energia Ltd. Workshop sobre inovação para o estabelecimento do setor de energia solar fotovoltaica no Brasil; 2011.

[38] MPX Energia Ltd. MPX - A company of the EBX Group; 2012. Available at: www.mpx.com.br Accessed on 23/07/2012.

[39] COELBA - Grupo Neoenergia, 2013. Available at: www.coelba.com.br/Pages/Sala de Imprensa/noticias.aspx Accessed on 24/02/2015.

[40] SEPLANDE - Secretaria de Estado do Planejamento e do Desenvolvimento Econômico / Estado de Alagoas. Aproveitamento de resíduo da cana é novo trunfo econômico de Alagoas. 2012. Available at: http://www.seplande.al.gov.br/sala-de-imprensa/noticias/2012/maio-2012/aproveitamento-de-residuo-da-cana-e-novo-trunfo-economico-de-alagoas Accessed on 13/04/2013.

[41] Eletrobras Eletrosul Gestor Digital da Informações Estratégicas. Empresas ameaçam sair de Belo Monte; 2010. Available at: http://www.eletrosul.gov.br/gdi/gdi/index.php?pg=cl_abre&cd=hhkZdb90{Okfk Accessed on 08/05/2012.

[42] EPE. Belo Monte Hydroelectric Dam Project Fact Sheet May 2011. Empresa de Pesquisa Energética (EPE); 2011.

[43] Santo Antônio Energia; 2012. Available at: http://www.santoantonioenergia.com.br/site/portal_mesa/pt/home/home.aspx Accessed on 08/05/2012.

[44] Eletrobras Eletronuclear, 2012. Available at: www.eletronuclear.gov.br Accessed on 04/07/2012.

[45] Ricarte E, Estefen S F. Avaliação Econômica E Ambiental De Usinas Para Extração De Energia Das Ondas Do Mar. Sociedade Brasileira de Engenharia Naval, 2003.

[46] COELBA. Tabela de Tarifa e Preço Final de Energia Elétrica; 2012.

[47] de Jong P. Economic, technical and environmental analysis of renewable and non-renewable electricity generation technologies in Brazil. Master's Dissertation – Escola Politécnica, Universidade Federal da Bahia (UFBA), Salvador; 2013.

[48] Diesendorf M. Sustainable Energy Solutions for Climate Change. UNSW Press, Sydney; 2014.

[49] Moriarty P, Honnery D. What is the global potential for renewable energy? Renewable and Sustainable Energy Reviews 2012; 16: 244-252.

[50] Scorah H, Sopinka A, Van Kooten G C. The economics of storage, transmission and drought: integrating variable wind power into spatially separated electricity grids. Energy Economics 2012; 34: 536–541.

[51] Crutzen P J, Mosier A R, Smith K A, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos. Chem. Phys., 8, 389–395, 2008.

[52] Garçon J. Santo Antônio liga turbinas, mas ainda está sem conexão. Brasil Economico; 2013. Available at: http://brasileconomico.ig.com.br/noticias/santo-antonio-liga-turbinas-mas-ainda-esta-sem-conexao_127457.html Accessed on 10/05/2013.

[53] Teixeira P A. Linhão de Belo Monte será em 800 kV e escoará energia para RJ e MG. Agência Canal Energia, 2012. Available at: http://www.canalenergia.com.br/zpublisher/materias/Retrospectiva.asp?id=89238&a=2012 Accessed on 15/05/2013.

[54] MME - Ministério de Minas e Energia (Brazil), EPE - Empresa de Pesquisa Energética. Estudos para a Licitação da Expansão da Transmissão - Programa de Expansão da Transmissão 2013-2017; 2013.

[55] de Jong P, Sánchez A S, Torres E A, Kalid R A. Energia Eólica, Solar e das Ondas no NE do Brasil: Análise de Parâmetros Meteorológicos em Relação à Demanda Elétrica. VII Congresso Nacional de Engenharia Mecânica, CONEM; 2012.

[56] de Jong P, Kiperstok A, Torres E A. Grid Connected Wind Power Penetration in the Northeast of Brazil. Brazil Windpower 2014 conference and exhibition, coletânea, 2014, Rio de Janeiro.

[57] de Jong P, Kiperstok A, Torres E A. Integration of variable renewable energy into the electricity grid in Bahia Brazil. Eficiência Energética e Produção de Energia Renovável Políticas, oportunidades e desafios para o mercado, para a ciência e para a educação. Guerra J B S O A, Leal W, Dutra L, Ladwig N I, Costa R S, editors. Florianópolis: Consórcio Projeto REGSA, 2014. pp. 259-278.

[58] Moura P S, Almeida A T de. Multi-objective optimization of a mixed renewable system with demand-side management. Renewable & Sustainable Energy Reviews 2010; 14: 1461-8.

CHAPTER 3

Integrating Large Scale Wind Power into the Electricity Grid in the Northeast of Brazil

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Integrating Large Scale Wind Power into the Electricity Grid in the Northeast of Brazil

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ABSTRACT

Wind power in the Northeast (NE) region of Brazil is currently undergoing rapid development and installed capacity is expected to exceed 16,000MW by 2020. This study examines the feasibility of integrating large scale wind power into an electricity grid (the Brazilian NE subsystem) which has a high proportion of existing hydroelectricity. By extrapolating existing wind power generation data, the maximum achievable wind power penetration (without exports to other Brazilian regions) and corresponding surplus energy is determined for the NE subsystem. The viable maximum penetration of wind energy generation in the NE subsystem was estimated to be 65% of the average annual electricity demand assuming that existing hydroelectric and gas generators have 100% scheduling flexibility. These results are compared to the actual gross penetration of wind power forecast to reach 55% in the NE subsystem by 2020. The overall Levelised Cost of Electricity (LCOE) is calculated for various scenarios where wind power replaces all fossil fuel generators in NE subsystem. It was concluded that by 2020, wind power could feasibly reduce the overall LCOE by approximately 46-52% and reduce CO_{2eq} emissions by 34 million tonnes per year compared to a power system with no new renewable generation.

Keywords: Renewable Energy; Wind Power; Hydroelectricity; Integration; LCOE.

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. Wind power at good locations in Brazil is already more competitive than coal-fired power generation [1]. The penetration of wind power will grow significantly in the Northeast region of Brazil, and particularly in the state of Bahia, Ceará and Rio Grande do Norte during the coming decades. According to the Wind Atlas of Bahia the state’s total wind power potential at a height of 80m above ground is estimated to be 39,000MW [2] which would be more than sufficient to supply the total electricity demand of the Brazilian Northeast region. However, as solar and wind power technologies are both variable technologies (that is, the amount of energy production cannot be regulated to match demand) the main difficulty is not with the amount of wind and solar resources available, but rather the smooth 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, weather forecasting, controlling hydroelectric plants on a sub-hourly basis to enable gap filling, interstate balancing and energy storage systems.

Wind power penetration, in terms of meeting electricity demand, is greater than 20% in a number regions and countries in the world including South Australia, Denmark, Portugal, Nicaragua and Spain where wind power met 40%, 39.1%, 27%, 21% and 20.4% of electricity demand in 2014, respectively [3, 4]. Therefore, wind power has the capability to provide a large proportion of supply, however, more research needs to be conducted on the practical challenges of large scale integration and storage for wind and solar power. This paper examines the advantages and challengers of integrating wind energy into electricity grids with high proportions of hydroelectricity and uses the Northeast region of Brazil as a case study.

1.1. Objectives

The main objective of this study is to evaluate the technical, economic and environmental advantages and disadvantages of integrating variable renewable energy technologies, such as wind power, into the Brazilian Northeast electricity grid and still reliably meet electricity demand. The theoretical maximum feasible penetration of wind energy in the states of Bahia, Ceará, Rio Grande do Norte and the entire Northeast subsystem will be estimated assuming that wind power will be combined with existing hydroelectric and gas plants and that curtailed energy should be kept to a minimum. Additionally, the percentage of electricity spilled for different penetrations of wind power in Brazil's Northeast subsystem will be calculated. Spilled or surplus energy is defined as the curtailed energy (such as excess wind or solar energy) that cannot be used to balance demand[8]. A small percentage of curtailed energy is tolerable for variable renewable sources and allows for higher penetrations. For example, when wind energy with surplus generation still proves to be cheaper than an alternative fossil fuel energy source. However, very large proportions of spilled renewable energy effectively mean that renewable generators are operating at a lower capacity factor which has the consequence of a loss in revenue.

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[8] In actual fact, there are always small amounts of spilled energy in a large electricity grid. These may be due to transmission line congestion, power system faults or load and weather forecasting uncertainty which result in differences between the actual load and hourly generator scheduling. For this reason the generation matrix has a specified spinning reserve to account for these small imbalances. However, these amounts of spilled energy are beyond the scope of this study.

The technical, economic and environmental ramifications of the total wind energy penetration projected for each state in the Brazilian Northeast subsystem by 2020 will also be examined. Finally the Levelised Cost of Electricity (LCOE) for the Northeast subsystem generation matrix is compared under various conditions, including scenarios where wind power replaces all fossil fuel generators.

The impact that large scale solar and wind energy have on the frequency and voltage stability and quality of a power system, for example during fault conditions, are discussed in detail by Shafiullah et al [5], Hossain et al [6] and Vilchez et al [7] and are beyond the scope of this study.

1.2. Justification

This study differs from many previous studies because it examines the integration of large scale wind power into a power system with a high proportion of existing hydroelectric generation. As wind power deployment in the Brazilian Northeast is predicted to increase substantially in the coming years, the power system will need to be adapted accordingly in order to optimally balance the different generation technologies available. Therefore, this study is very important in a regional context, as it will help power system planners assess the impact of large scale wind penetration and identify where and how the power system needs to be upgraded.

The electricity supply matrix for Brazil in terms of installed capacity consists of 62% hydroelectricity and about 5.6% imported energy which is mostly hydroelectricity from Paraguay [8]. However hydroelectric potential near populated and industrialized areas is almost entirely saturated in most regions of the country. There are proposals for new large hydroelectric reservoirs in the remote Amazon and Cerrado river basins, but such developments will have high environmental, investment and transmission line costs [9] and cause significant greenhouse gas emissions from decaying rainforest flooded by the reservoirs [10].

The Northeast (NE) region of Brazil receives only a fraction of the annual total national rainfall [11, 12] and the NE's hydroelectric reservoirs, which are located in the São Francisco basin (one of the driest regions in the country), are already over exploited. As a result of a drought which began in 2012 in the NE of Brazil, in 2013 hydroelectricity only contributed

41.9% of the total electricity demand in the NE subsystem (as shown in table 1). The shortfall was supplemented by thermal power generation and *imported* electricity from other Brazilian regions contributing 28.8% and 25.7%, respectively, while wind energy contributed only 3.6% [13]. This is a marked difference to the situation in 2011 where hydroelectric generation contributed more than 70% of the total electricity demand in the NE [13]. Nevertheless, even in a drought year, the large proportion of hydroelectricity in the grid allows for substantial system balancing flexibility. The operational flexibility of a power system is its technical ability to quickly modulate electricity generation supplying the grid and outflows on the demand-side to effectively achieve a power balance within a specific grid area [14].

Table 1: Electricity generation sources supplying Brazil's NE subsystem from 2011 to 2014. "Imported" electricity consists mostly of hydro from Brazil's Southeast and North subsystems. Source ONS [13].

	2011	**2012**	**2013**	**2014**
Hydroeletric	70.6%	67.5%	41.9%	39.1%
Wind	1.8%	3.0%	3.6%	6.4%
Thermal	8.0%	14.1%	28.8%	40.1%
Imported	19.6%	15.4%	25.7%	14.4%

Climate change mitigation will increase the demand for emissions free electricity generation such as the use of more hydropower [15]. However another effect of climate change is that the hydroelectric potential in the São Francisco basin will be reduced due to more frequent and intense climate induced droughts [16, 17]. Therefore energy storage provided by hydro reservoirs will be ideal for integrating intermittent wind power resources which can replace the lost hydroelectric energy [15]. Significant increases in wind power penetration would enable more water to be stored in the São Francisco basin. In November 2014 water levels in the São Francisco basin fell to their lowest levels in 13 years with only 13% of the total capacity remaining in terms of stored energy [13].

In 2014 6.4% of the Brazilian Northeast's electricity was generated from wind power, however, as a result of the continuing drought, more than 40% of the NE's electricity was generated from thermal power sources [13]. Furthermore, approximately 6000MW of new thermal power plants are planned for construction or already under construction [8]. According to de Jong et al [12], there is a huge potential to substantially increase the penetration of wind and solar power in the NE region because average wind speeds and solar radiation levels are the highest in the country. This would offset the need for unsustainable fossil fuel power generation and *imported* electricity from other regions of Brazil. Currently only 15MW of photovoltaic (PV) is connected to the national grid [8], however, as a result of the national energy auctions, an additional 2180MW of PV capacity have been contracted for construction [8, 18]. A total of 5740MW of wind power capacity was finally contracted in the NE during the 2013 and 2014 energy auctions [18]. Together with those wind farms already planned for installation, if all newly contracted wind farms programmed for installation by 2019 are commissioned by 2020[9], this will see the total installed capacity of wind power in the NE region grow to more than 16,400MW, which is more than 5 times the 2014 installed capacity [8, 18].

2. BACKGROUND

2.1. Variable renewable energy integration

Mai et al [19] and Elliston et al [20] show that generation configurations where variable renewable energy (including wind and solar PV) supply up to 50% and 70%, respectively, of electricity demand are technically feasible. Additionally Elliston et al [21] argue that conventional base-load power stations are unnecessary and instead demand can be reliably supplied by a power system with large penetrations of variable renewable sources with large geographical diversity and a large capacity of peak-load generators such as hydroelectric and gas plants. Likewise Mason et al [22, 23] demonstrated that 100% of New Zealand’s electricity generation can viably be supplied by renewable energy sources, even considering the driest year on record. The proposed generation mixes included installed capacities of up to 60% hydroelectricity, 14% geothermal and 25% wind power where wind power was capable of replacing an equivalent amount of fossil fuel capacity. Purvins et al [24] found that large scale integration of wind farms in Latvia (where a large penetration of hydroelectric plants already exists) would result in a reduced probability of power deficits in winter, but would also increase power surplus in the spring. Scorah et al [15], Eichman et al [25], Pete et al [26], Nikolakakis & Fthenakis [27] and GE Energy [28] demonstrated that in electricity networks which have low percentages of hydroelectricity and high percentages of inflexible coal power generation, it is still possible to include 25-35% of variable renewable energy with limited

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[9] In the past, the completion of a number of wind farms (and other power generation projects) in Brazil has been delayed, in some cases several months behind schedule. Therefore, in this study it is assumed that the commissioning of wind farms and their respective transmission lines could be delayed up to 12 months, Hence, it is assumed that all wind farms currently contracted to commence operation in 2015-2019, will be generating power for the NE subsystem by 2020.

curtailment. However, in general these studies also concluded that as the percentage of variable renewable penetration increases, so do the costs of integrating these resources into the grid due to the requirements of transmission system upgrades, and operational reforms (such as the implementation of accurate weather forecasting, sub-hourly scheduling and increased balancing area cooperation).

However the detailed study by GE Energy [28] found that with 35% variable renewable penetration across the Western Electricity Coordinating Council region of the USA, network operating costs would drop by $20 billion per year from approximately $50 billion per year, resulting in a 40% reduction due to offset fuel costs and emissions reductions (given the fuel prices and carbon tax assumed for the study of $2/MBTU coal, $9.50/MBTU gas and $30/ton CO_2). Additionally Eichman et al [25] and GE Energy [28] calculated that variable renewable penetrations of 34-35% would reduce CO_2 emissions by up to 45%.

Compared to dispatchable sources of electricity generation, wind power is less valuable to system operators because of its uncontrollable nature [29]. System operators often treat variable renewable electricity generation such as wind power, as negative load and therefore the concept of net load is used by various studies [19, 26, 27, 28 30]. The net load is defined as the electricity load net wind power, or electricity load minus variable generation. The flexible proportion of a generation matrix can be scheduled to follow the net load rather than follow the load.

Due to operational ramp rate constraints of coal and nuclear base-load generation, the optimal mix of generation technologies combined with high penetrations of wind energy occurs when base-load generation is replaced with mid and peak load generation technologies [31]. Denholm & Margolis [30] found that surplus PV generation becomes increasingly large above PV penetrations of 10-20% in the Texas electricity power system due to the inflexible nature of base-load generation and because PV output is only available during a relatively narrow daily envelope.

In comparison to the coal dominated electricity grids in the USA, the percentage of inflexible coal and nuclear power base-load generation in Brazil is very low (approximately 4%). Therefore, it is predicted that greater penetration of wind power could be achieved in Brazil because the majority of electricity (almost 80%) is generated from flexible hydroelectricity [8, 13]. Nevertheless, by the end of the decade, hydroelectricity may only contribute 40% of the Brazilian NE region’s electricity supply, due to increased demand, climate change and the effects of droughts. It will be shown that 55% of electricity demand could be supplied by wind power (a variable renewable energy source) instead of relying on fossil fuels. The remaining 5% could quite feasibly be generated from biomass. The technical and economic feasibility of this unique generation matrix is investigated in this study.

2.2. Variable renewable energy integration in Brazil

While there are several international studies that examine the integration of large scale variable renewable energy, there are very few studies that focus on the Brazilian region. Borba et al [32] propose utilising demand-side management to store excess wind energy generated in the Northeast of Brazil by implementing a fleet of 1.6 million plug-in hybrid electric vehicles. However this proposal would be quite costly compared to storing excess energy in Brazil’s existing hydroelectric infrastructure which has a large amount of daily storage and dispatch flexibility and to some degree, seasonal storage flexibility as well [33].

Gárdos et al [34] contend that measures including transmission system upgrades, sub-hourly scheduling and accurate weather forecasting are needed to minimise curtailment and the impact of wind power variability. Additionally, Gárdos et al [34] found that the operation of sugar cane biomass generators in Brazil have a seasonal complementarity with the hydroelectric reservoirs because the sugar cane harvest season (April – October) happens to correspond to the dry season during which the hydroelectric water reservoir levels decrease. A similar seasonal complementarity exists between conventional hydroelectric availability and variable renewable resources (solar and wind power) in the Brazilian Northeast region [12].

According to the Wind Power Atlas of Bahia, there are a number of areas in the interior of the state with annual average wind speeds of 8-10m/s and additionally, the Weibull shape factor, k, exceeds 3 in vast regions of the state and in some areas even exceeds 4 [2]. These high k values for the Weibull probability distributions of wind speeds in the interior of Bahia indicate the predominance of very consistent wind speeds around the mean wind speed. This means that in addition to having high average wind speeds, the frequency of extreme low and high wind speeds, which fall outside the operational range of typical wind turbines, is very rare. Therefore these regions in Bahia are ideal for wind power generation with excellent annual capacity factors.

The downside of the wind regime in the interior of Bahia is that higher average wind speeds occur late at night and therefore the majority of wind power potential occurs between 20:00h and 08:00h, as can be seen in figure 1.

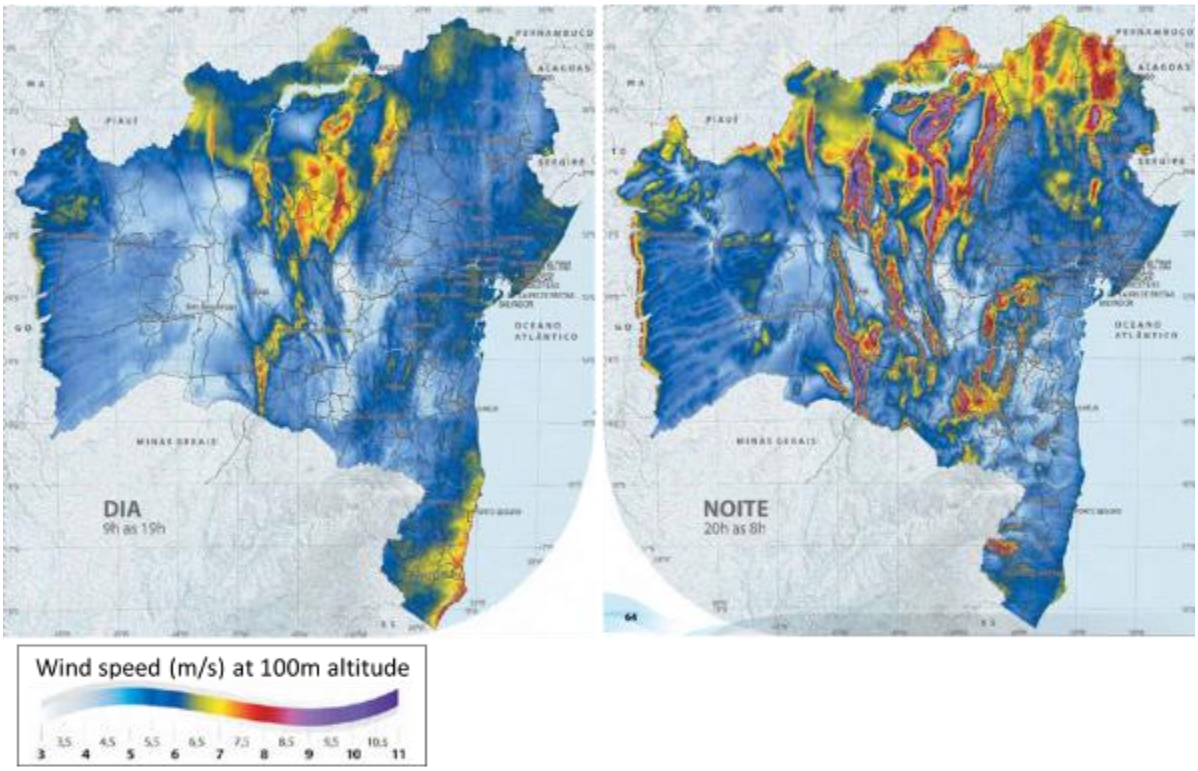

Figure 1: Wind Power Potential in Bahia (LHS: daytime; RHS: night-time). Source: Schubert [2].

2.3. Levelised Cost of Electricity (LCOE) in Brazil

A study Pereira Jr et al [35] examines the average generation cost and penetration of various renewable (and non-renewable) energy sources in the Brazilian electricity matrix, however, more recently the LCOE of wind energy has dropped significantly. The Câmara de Comercialização de Energia Elétrica / Brazilian Chamber of Electricity Trading (CCEE) [18] electricity auction sale prices provide a good indication of the cost of electricity from different sources of energy and roughly equate to the LCOE plus a profit margin. However, neither the auction prices, nor the study by Pereira Jr et al [35] incorporate the additional costs of extended transmission lines and environmental externalities. The international report by the Nuclear Energy Agency (NEA) International Energy Agency (IEA) and Organisation for Economic Cooperation and Development (OECD) [36] has LCOE data comparing traditional generation technologies in Brazil, but the analysis does not include the LCOE for wind power in Brazil or externalities. Research by de Jong et al [1] specifically focusses on the LCOE of various generation technologies in Brazil and the majority of the case studies used in the analysis are located in the Northeast region. The study also estimates the aggregate LCOE with the component costs of environmental & social externalities, as well as extended transmission line externalities for each generation technology. Specifically, the social (health damage) costs of particulate, SO2 and NOx pollution and environmental damage costs of life-cycle greenhouse gas (CO_{2eq}) emissions from fossil fuel, hydroelectric and other renewable power plants are calculated per MWh of electricity produced. (The cost of greenhouse gas damage adopted in the study was $25-30/tCO2eq) [1]. Similarly the losses and costs of extended transmission systems (those with lengths in excess of 2000km used to connect new hydroelectric plants to the grid) are also calculated and included as a component of the LCOE. As can be seen in figure 2, the LCOE varies significantly depending on the type of generation technologies. In this paper, the LCOE results shown in figure 2 (both with and without social and environmental externalities) will be used to estimate the annual cost of electricity in the Northeast subsystem.

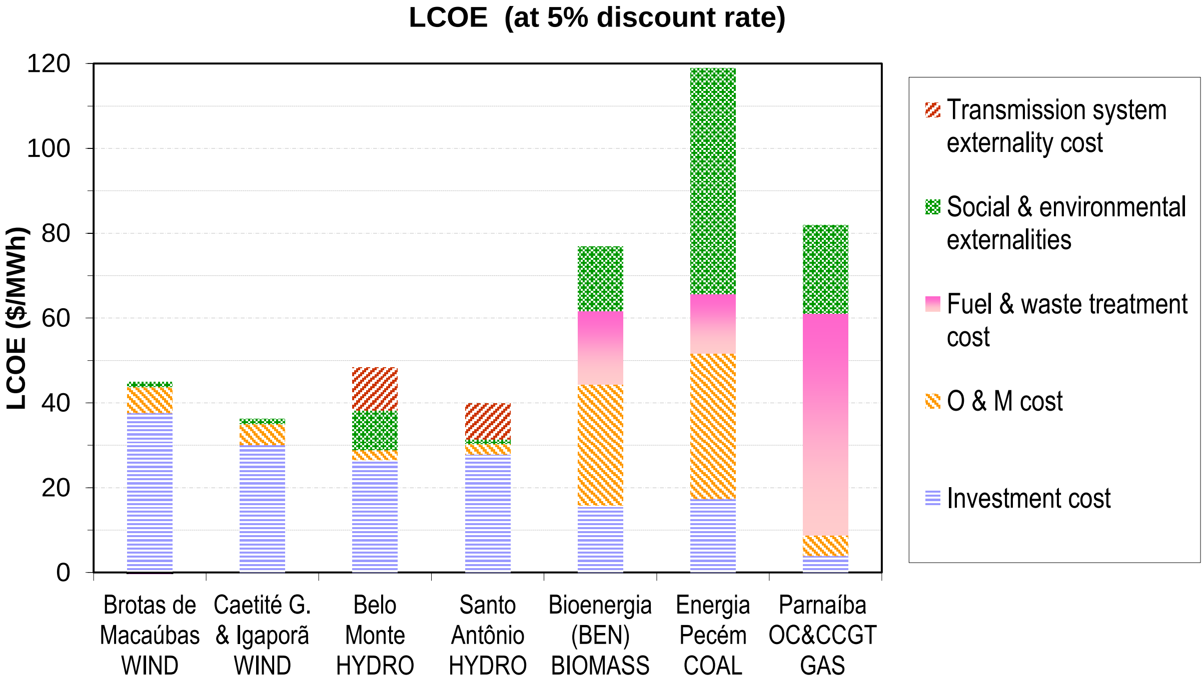

Figure 2: Levelised Cost of Electricity (in US$) with extended transmission line costs and environmental externality costs for various case studies supplying electricity to the Northeast region of Brazil. Source: de Jong et al [1]. (Note: The LCOE from wind energy is low due to the excellent capacity factors for wind farms in the NE region. Additionally, the transmission system costs for new hydroelectric plants are quite substantial due to the remote locations of these plants).

3. METHOD AND MATERIALS

3.1. Wind power penetration and simulation of spilled energy

Previously published research [37] which estimated the maximum penetration of wind power in Bahia is expanded to also include the Brazilian NE states of Ceará and Rio Grande do Norte. Figure 3 shows the NE region and the locations of the 16 wind farms considered in the study. In figure 3, it can be observed that most of the wind farms are spread over a large geographical area with those located in central Bahia are over 1000km from the coastal wind farms in Ceará.

Figure 3: Northeast region of Brazil, Northeast subsystem, Ceará (CE), Rio Grande do Norte (RN), Bahia (BA) and location of wind farms used in the study. (Note: Maranhão is not included in the Brazilian Northeast subsystem).

Hydroelectric and gas turbines are typical examples of flexible load-following plants which can rapidly ramp up (or down) supply to balance demand [38]. Brazil's NE matrix (not including wind power) predominantly consists of flexible hydroelectric and agile gas (and oil) turbines. However, hydroelectric dams serve multiple functions including irrigation, flood control, fish habitat and recreation that can constrain their use for purely system balancing [26]. Similarly, due to ecological reasons, the São Francisco River has minimum flow rates and this can limit the minimum hydroelectric generation to non-zero. Nevertheless it is assumed that the NE power system’s spinning reserve margin is larger than the minimum hydroelectric generation necessary to maintain the minimum flow rates of the São Francisco River. Furthermore, these ecological constraints generally occur on different time scales to those required for wind hydro integration [39]. Currently there is approximately 12,000MW of hydroelectric capacity operating in the NE region (including 10,000MW along the São Francisco River) [8]. It is anticipated that even during drought periods, this enormous amount of hydroelectric capacity, given its inherent flexibility to modulate output, can be utilised to balance the day to day hourly variations in net load (as a result of stochastic wind power variations). While there are 2 inflexible coal power stations in Ceará, they make up less than 5% of the total installed generation capacity in the NE subsystem and in the future these could be displaced by cheaper and cleaner wind farms. Therefore, in this study it is assumed that the NE generation matrix has 100% flexibility and can be scheduled to follow variations in the net load curve (defined as the hourly electricity load minus wind power).

Transmission line losses and congestion issues as a result of wind power are not considered in this study. However, transmission lines will need to be expanded and upgraded to accommodate the expected increase of wind power penetration in the NE matrix. This issue is addressed by Porrua et al [40], Gárdos et al [34] and Fleury et al, [41].

The average summer and winter 24 hour diurnal (daily cycle) load curves for the Brazilian NE subsystem were taken from Operador Nacional do Sistema Elétrico [42] data. Figure 4 shows the NE diurnal load curve for both summer and winter and it can be observed that the average winter load is approximately 10% less than the summer load. By combining this 24 hour load curve data with average monthly load data (see figure 8) [13] diurnal load curves were derived for each month of the year. The curves were normalised to the average summer maximum load and used to represent the hourly electricity demand of the states of Bahia, Ceará and Rio Grande do Norte.

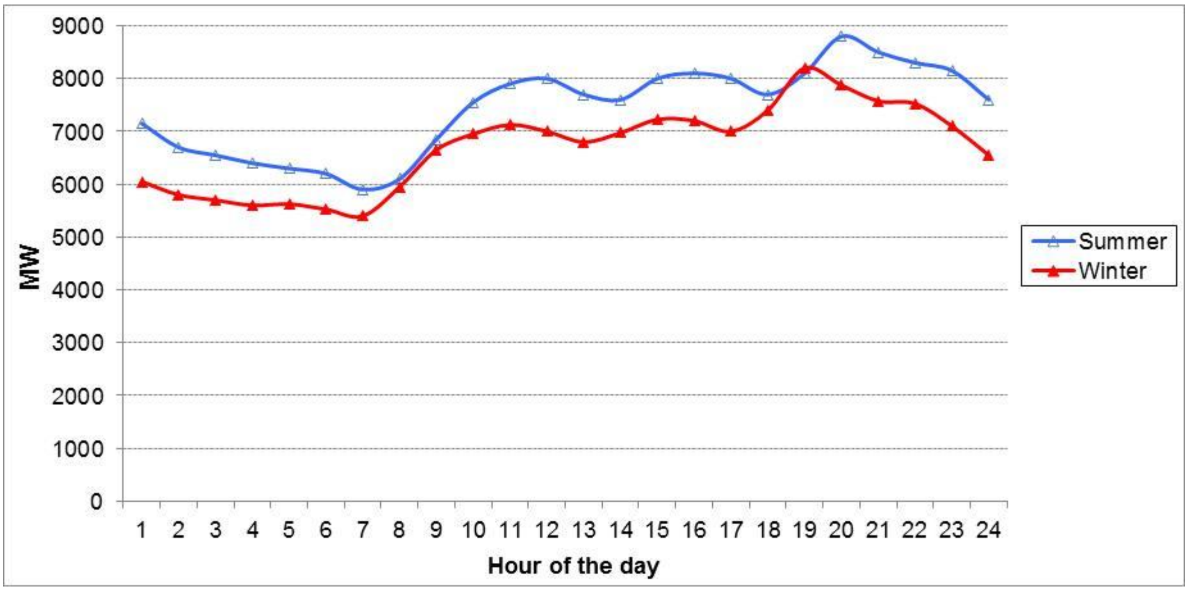

Figure 4: Average hourly load curve profile for the NE region of Brazil for a typical summer and winter day. Source: ONS [42]. It should be noted that the average hourly load curves do not take into account reduced peak loads on Sundays and public holidays.

Average hourly, daily and monthly wind power data from the Operador Nacional do Sistema Elétrico / Brazilian National Electricity System Operator (ONS) [43, 44] for grid connected wind farms in Bahia, Ceará and Rio Grande do Norte was examined. Additionally detailed hourly wind power generation data (MWaverage) for each hour of 2013 for 6 wind farms in Bahia (including 3 wind farms located in Brotas de Macaúbas), 4 wind farms in Ceará and 6 wind farms Rio Grande do Norte was obtained courtesy of the ONS and Brennand Energia. All these data values were examined for anomalies and any outliers or missing measurements were replaced with the mean hourly value of the month in question. The hourly wind generation data for each of these states was aggregated and normalised to the total installed capacity of each state, thus yielding the hourly capacity factor for each state. Then the weighted average of the hourly wind power capacity factor from Bahia, Ceará and Rio Grande do Norte was calculated considering the proportions of each state's total average wind power production forecast for 2020 (see table 3).

The September diurnal (average hourly) wind power capacity factor curves for Bahia, Ceará, Rio Grande do Norte and the curve for their weighted average are shown in figure 5. The month of September was chosen because the wind energy capacity factor in Brazil's NE region is typically highest in the month of September [45].

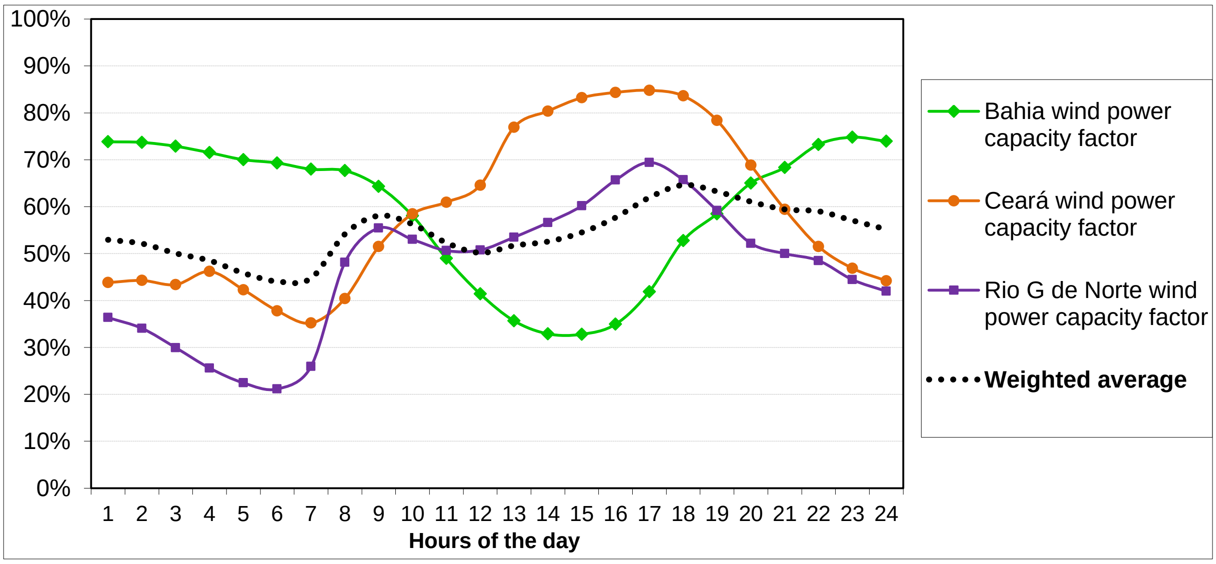

Figure 5: Average hourly wind power capacity factors in Bahia, Ceará and Rio Grande do Norte for September 2013. Source: ONS and Brennand Energia (2013).

It can be observed that the diurnal (average hourly) wind power generation profile in Bahia drops to its lowest level during the mid-afternoon hours of the day and therefore does not match well with the NE load curve. On the other hand, the diurnal wind power profile of the coastal wind farms of Ceará and Rio Grande do Norte, which peaks between 16:00 and 19:00h, correlates very well with the NE load curve.

By analysing the hourly diurnal and monthly wind power capacity factor data in Bahia, Ceará and Rio Grande do Norte during all of 2013, the viable maximum wind energy penetration is calculated for each of these states. This was done by iteratively increasing the percentage of wind energy penetration until the lowest point in the diurnal net load curve (for the month of September) is reduced to zero. In the same manner, the impact of increasing wind power penetration in the NE’s electricity grid can also be estimated. It can be observed from table 3, that by 2020, the large majority (more than 80%) of the installed wind power capacity in the Northeast subsystem will still be located in Bahia, Ceará and Rio Grande do Norte [8, 18]. Therefore, the weighted average data of these three states’ hourly wind power capacity factor was utilised to represent wind power production in the entire NE subsystem. This enabled the simulation of wind power penetrations of 45%, 55%, 65%, 75%, 85% and 100% in the NE subsystem. For each of these penetrations, the net load curve (that is, hourly load minus hourly wind power) and spilled wind energy are calculated for each hour of the day for an entire year. The nominal wind power capacity for different wind penetrations was calculated from the NE average (Avg) annual load and capacity factor as follows:

$$\text{Nominal Wind Capacity} = \text{Penetration} \times \text{Avg Load} / \text{Avg Capacity Factor}$$

Then the hourly net load for each hour of the year was calculated as follows:

$$\text{Hourly Net Load} = \text{Hourly Load} - \text{Hourly Capacity factor} \times \text{Nominal Wind Capacity}$$

Therefore:

$$\text{Hourly Net Load} = \text{Hourly Load} - \text{Hourly Capacity factor} \times \text{Penetration} \times \text{Avg Load} / \text{Avg Capacity Factor}$$

Energy was defined as spilled or surplus if the hourly net load was less than zero. Therefore the total spilled energy is the sum of the net load for each hour where it was less than zero and the average spilled energy as a percentage of the load and as a percentage of wind energy can be calculated as follows:

$$\%\ \text{Spilled Energy} = -\{\Sigma_{hour}\ (\text{Net load}_{hour}),\ \text{if Net load}_{hour} < 0\} \times 100 / (\text{no. of hours} \times \text{Avg Load})$$

Therefore:

$$\text{Spilled Wind Energy as a percentage of total wind energy} = \%\ \text{Spilled Energy} / \text{Penetration}$$

The viable maximum wind energy penetration before significant curtailment occurs can then be estimated for the NE subsystem. Curtailment was considered insignificant if the annual surplus wind energy was less than 1%. Wind energy may still be viable with larger amounts of surplus energy, however the cost increases proportionally to the curtailed amount. Similar to the method used by Denholm & Margolis [30], surplus wind energy for the NE subsystem is plotted against increasing amounts of wind power penetration.

3.2. Installed wind power by 2020 and Levelised Cost of Electricity in the NE of Brazil

By using data sourced from Agência Nacional da Energia Elétrica / Brazilian National Electricity Agency (ANEEL) [8] and CCEE [18], the total installed wind power capacity by 2020 for each state in the NE of Brazil is estimated. Based on these predictions the average wind power generated by each state is then calculated using measured and predicted capacity factor data. The ONS and Brennand Energia wind power data was used to calculate the capacity factors for Bahia, Ceará and Rio Grande do Norte. For the other states in the NE subsystem, where generation data was not readily available, the capacity factors were calculated from ANEEL [8] and CCEE [18] projections of the average wind power for each wind farm, which is stated in the power purchase agreements. It is worth noting that the projected capacity factor for a number of older wind farms (particularly in Rio Grande do Norte) has been over estimated in power purchase agreements in the past. The predicted electricity demand for each state by 2020 was calculated from the ONS [42] and ONS [13] data sources by extrapolating the annual growth in demand from 2005-2014 of 4.1%. Finally the expected gross wind power penetration for each state in the NE by 2020 was calculated by dividing the average wind power generation by the respective electricity demand. The results are summarised in table 3.

The average LCOE in the Northeast subsystem and the overall cost to generate electricity in 2014 is calculated for each generation technology that contributes to the NE generation matrix considering the current generation matrix and a 100% renewable generation matrix in 2020. LCOE data including and excluding social and environmental externalities (see figure 2) is taken from de Jong et al [1]. Social externalities are estimated health damage costs from pollution and environmental externalities are greenhouse gas damage costs. The LCOE (with and without externalities) of diesel/oil power stations is assumed to be the same as that of coal fire power stations. Electricity generation data is taken from the ONS [13]. Similar to the approach taken by Elliston et al [20, 46], the electricity generation cost of the current system is compared to a system where wind power replaces all thermal power (fossil fuel and biomass) generators and *imported* thermal electricity from other Brazilian regions. Based on ANEEL [8] data for the installed capacity of thermal power generators in the NE subsystem, it is assumed that electricity generation from thermal power is generated from 40% gas, 40% diesel/oil/coal, and 20% biomass resources. *Imported* electricity is assumed to be generated by 80% hydroelectricity, 19% thermal power and 1% nuclear power and is subject to transmission line costs and losses.

4. RESULTS

4.1. Maximum wind power penetration in Bahia, Ceará and Rio Grande do Norte

Given that during the winter months of the year the Brazilian NE's electricity demand is less and wind production is greatest (particularly during the month of September), it is during this month that there would be an upper limit for wind power penetration without storage. Figure 6 shows the normalised NE load curve and the net load curve for Bahia, Ceará and Rio Grande do Norte.

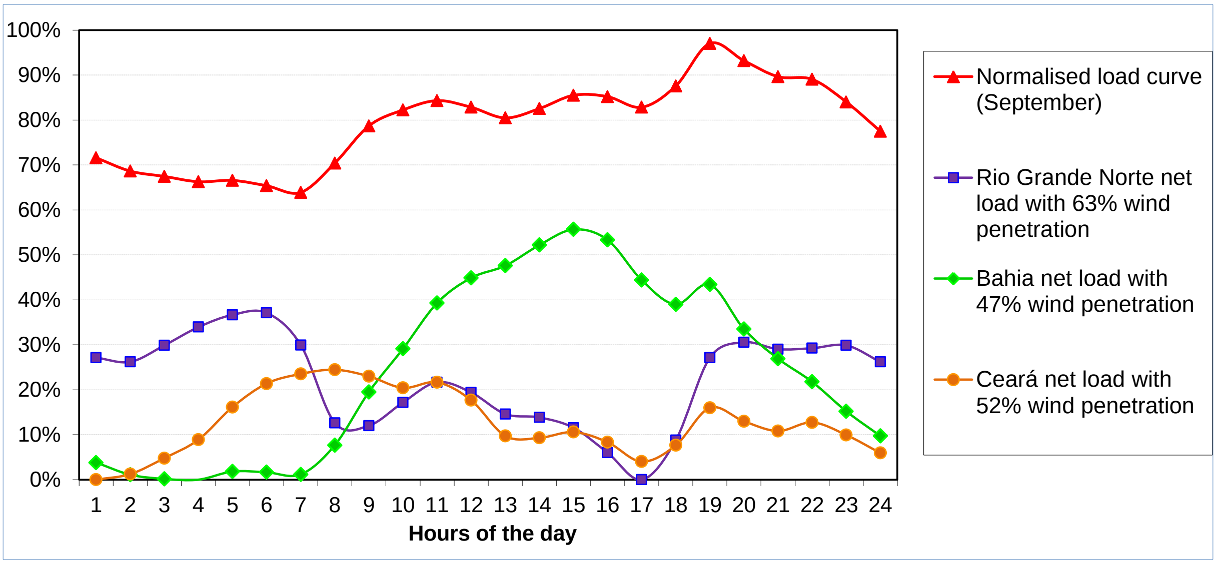

Figure 6: Brazilian NE average hourly load curve and net load curves (load minus wind) for Rio Grande do Norte, Ceará and Bahia in September 2013.

In the state of Bahia the maximum annual wind energy penetration limit was estimated to be 47% for electricity generated from wind power before significant curtailment occurs. Considering the average net load curve (hourly electricity load minus average hourly wind power) for a 24 hour day in September there would be zero curtailed energy. However, given the stochastic nature of wind intermittency, if the aggregate wind power in Bahia diverges above its average diurnal curve between 1:00h and 7:00h it is likely that some curtailment would be necessary.

In the states of Ceará and Rio Grande do Norte higher penetration limits for wind energy are expected, because the diurnal wind power profile in the coastal regions of these states correlates very well with the NE region load curve. It was calculated that the maximum annual wind energy penetration was 52% and 63% for Ceará and Rio Grande do Norte, respectively. That is, with these annual wind penetrations, the lowest point in the net load curve just drops to 0 during September (the month wind energy production is at its highest). Due to the stochastic nature of wind intermittency, it is likely that some small curtailment of wind energy would occur, particularly in the months of September and October around 1am for Ceará and 5pm for Rio Grande do Norte. However, it should be noted that there would only be surplus wind energy during these hours when the aggregate wind power diverges above its average generation.

When such over production of wind power eventuates, it could be readily *exported* to other states given there is already substantial transmission infrastructure between states. However, with very large amounts of excess wind power production, the NE region's transmission system would need to be reinforced to allow for the increase in *exported* and *imported* energy between states.

4.2. Maximum wind power penetration in Brazil's NE region overall

Studies by Sinden [47] and Hoicka & Rowlands [48] found that increasing the number of renewable energy sources such as wind and solar power across various geographical locations significantly smoothed out power generation and produced less variability. This finding is supported by ONS [43, 44] data which shows that no two wind farms operating in different municipalities in the Brazilian NE region recorded the same maximum hour of wind generation. As wind power capacity increases across different locations in the NE region, it is expected that the variability and extreme instances of highs and lows of wind generation will be further reduced.

By 2020 the states of Bahia, Ceará and Rio Grande do Norte will have installed wind power capacities of 4744MW, 3024MW and 5663MW, respectively, and together these states will comprise more than 80% of the total wind power capacity in the Brazilian NE subsystem [8, 18]. Combining the average hourly wind power generation from these 3 states results in a complementarity and the maximum wind penetration for the entire NE subsystem can be roughly estimated. Therefore (based on each state's average wind power output projected for 2020) the weighted average of the hourly wind power capacity factor data was calculated as per the profiles shown in figure 5. Thus, an approximation of the hourly wind capacity factors for the entire NE subsystem was obtained and used to estimate the net load curve for different penetrations of wind power in the NE region.

The NE load curve, diurnal average wind capacity factor curve and the diurnal average hourly net load curve results for the month of September are shown in figure 7.

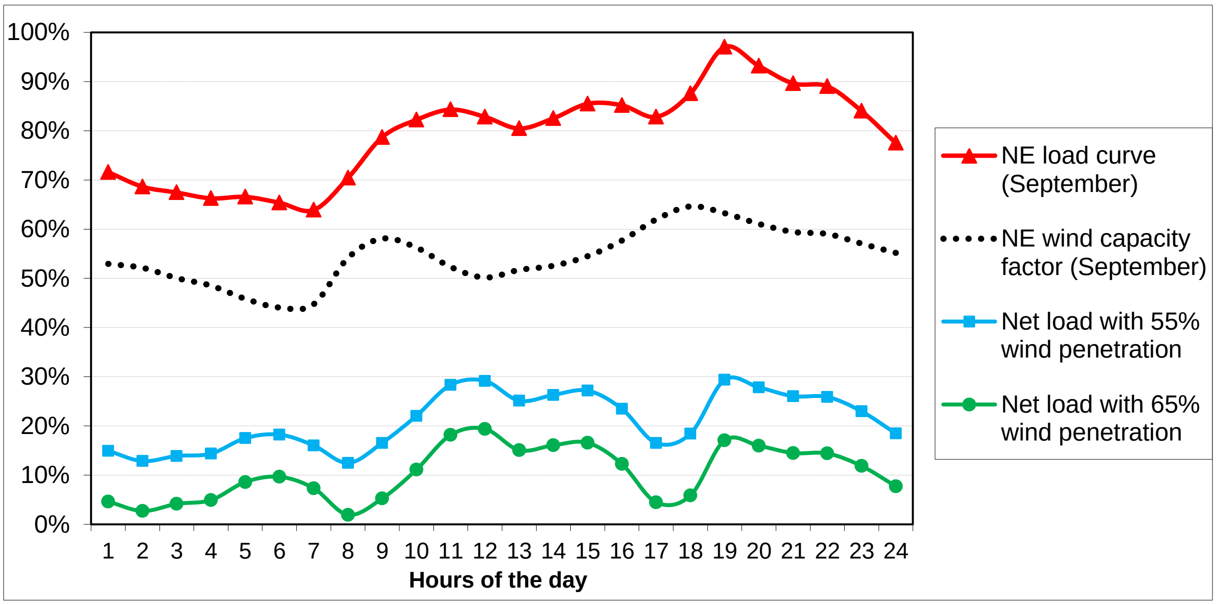

Figure 7: Brazil's NE load, diurnal average wind capacity factor curve and net load curves (load minus diurnal average wind power with annual wind penetrations of 55% and 65%) for September 2013. (Note: As the net load curves are greater than 10% from 10:00-16:00h, even with wind energy penetrations of 55- 65% a small percentage of solar PV could also be integrated in the NE subsystem without causing significant curtailment).

With 31% wind penetration all wind farms in the NE could operate at any hour of the day up to their combined installed capacity (or at a capacity factor of 100%) and no electricity would be curtailed. Assuming, that the dispatchable generators (which include hydroelectric and gas power plants) in the NE power system are 100% flexible, then the viable maximum wind energy penetration for the NE region is estimated to be 65%. This would result in less than 1% of curtailed energy. If the flexibility of the dispatchable generators is constrained to less than 100% due to operational ramp rate limits, then wind power penetration without curtailment would be reduced proportionally. For example, if the overall flexibility of the NE power system's hydroelectric and gas plants is reduced to 85%, then wind power penetration would be limited to 55%.

These high percentages of wind penetration without storage or significant amounts of curtailed energy are a unique result when compared to previous studies which investigate the wind and/or PV penetration of other regions. The reason for this is that the diurnal (average hourly) wind power capacity factor curve for the Brazilian NE region closely correlates with the NE hourly load curve (see figure 7). In fact, it is estimated that the viable maximum wind energy penetration specifically for the month of September is 87% which further emphasises this strong correlation. Therefore, the main reason that wind energy penetration is limited to only 65% annually is because the average monthly wind energy output in the NE region for a typical calendar year does not have a very strong correlation to the annual load curve.

This can be observed in Figure 8, which shows the 2014 monthly wind energy capacity factors for the NE subsystem compared to the average stored hydroelectricity available in the São Francisco basin and NE subsystem average monthly load. Nevertheless, figure 8 also demonstrates that there is a strong seasonal complementarity between hydroelectric availability and wind power production. That is, average wind power generation is high during the months when stored hydroelectric energy declines to its lowest level. Therefore large scale wind power will help to save water in the São Francisco basin, particularly during periods of water scarcity at the end of the dry season, and improve energy and water security.

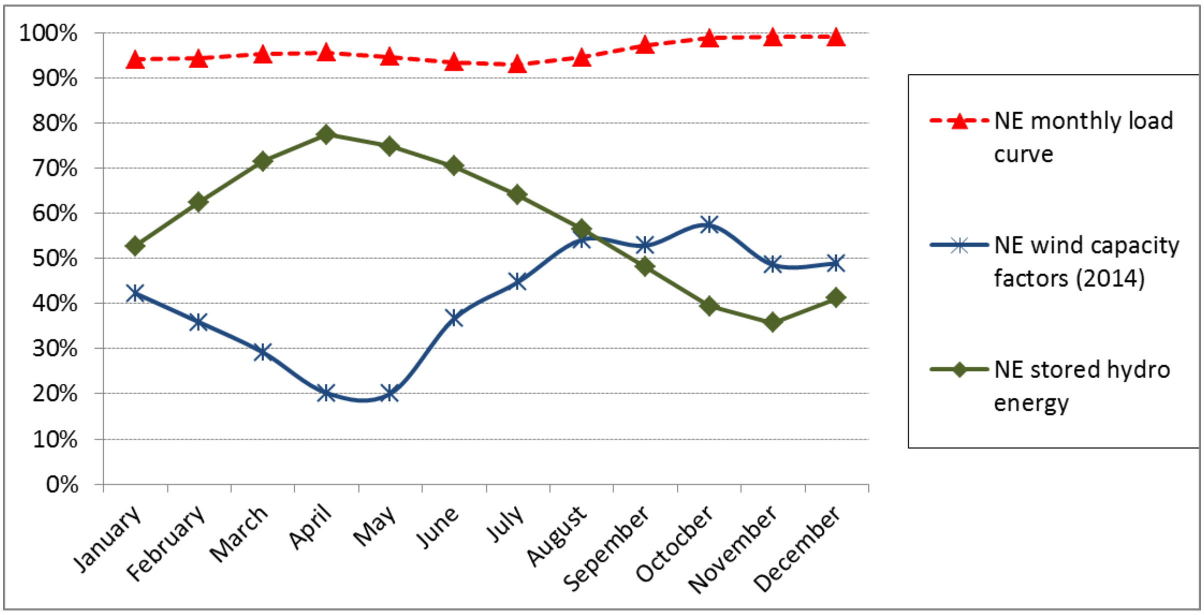

Figure 8: Brazilian NE average monthly load curve [13], long-term average monthly hydroelectric storage [13] and monthly wind energy capacity factors [45]. (Note: Monthly capacity factor data considers all wind farms connected to the NE subsystem grid in 2014 and that were operated in conjunction with the ONS).

There is also a seasonal complementarity between NE wind power and hydroelectric storage in the neighbouring North and Southeast regions of Brazil, however, wind farms in the South region do not have a seasonal complementarity with hydroelectric storage in the South region.

4.3. Spilled wind energy for high penetrations of wind power in the NE region of Brazil

By using the detailed wind generation data provided by Brennand Energia and the ONS, the capacity factors and spilled wind energy were simulated for each hour of the day for an entire year. The percentage of spilled wind energy was calculated for wind energy penetrations of 45-100% and the monthly and annual results are shown in table 2.

Table 2: LHS: 2013 monthly and annual wind power capacity factors in the Brazilian NE subsystem. RHS: Simulation of spilled wind energy (as a percentage of monthly and annual wind energy) for various wind energy penetrations in the NE subsystem.

	Capacity factors	**Pecentage of spilled wind energy with annual wind energy penetrations of:**					
		45%	**55%**	**65%**	**75%**	**85%**	**100%**
January	36.8%	0.00%	0.00%	0.02%	0.55%	2.71%	8.57%
February	41.7%	0.00%	0.00%	0.12%	1.51%	5.71%	14.62%
March	35.3%	0.00%	0.00%	0.01%	0.48%	2.18%	7.11%
April	24.3%	0.00%	0.00%	0.00%	0.00%	0.08%	1.01%
May	29.2%	0.00%	0.00%	0.00%	0.00%	0.14%	1.82%
June	35.4%	0.00%	0.00%	0.04%	0.35%	1.92%	7.06%
July	39.3%	0.00%	0.00%	0.05%	0.92%	3.36%	9.55%
August	50.9%	0.00%	0.05%	1.35%	6.06%	12.96%	23.89%
Sepember	54.5%	0.00%	0.21%	2.58%	8.73%	16.41%	26.92%
Octocber	52.6%	0.00%	0.32%	2.46%	7.24%	13.96%	24.29%
November	48.0%	0.00%	0.00%	0.23%	2.36%	7.14%	17.40%
December	33.4%	0.00%	0.00%	0.03%	0.32%	1.21%	5.68%
Annual	**40.1%**	**0.00%**	**0.06%**	**0.75%**	**2.99%**	**6.84%**	**14.26%**

It is estimated that with a wind energy penetration of 45% of the Northeast subsystem annual load, there would be zero spilled energy. With a wind penetration of 55%, spilled energy would still be negligible (0.06% annually as a percentage of the total generated wind energy).

Considering the theoretical viable maximum wind energy penetration limit of 65% estimated for the Northeast subsystem in section 4.2, there would be 0.75% of spilled wind energy annually and 2.58% and 2.46% of spilled wind energy specifically during the months of September and October, respectively. As expected the spilled wind energy during the other months of the year was even less.

Above a wind energy penetration of 65%, increasing amounts of energy would need to be curtailed unless this surplus energy can be *exported* to other Brazilian subsystems. With gross wind energy penetrations of 75% and 85% in the Northeast subsystem, it is estimated there would be 2.99% and 6.84%, respectively, of spilled wind energy annually and 8.73% and 16.41%, respectively, of spilled wind energy specifically during the month of September.

If the excess wind energy cannot be *exported* or stored, then the net penetration of wind energy contributing to the grid (for high wind penetrations) is reduced by the curtailed or spilled amount. That is, the net wind energy penetration is the gross penetration less the spilled energy (as a percentage of the total load). This can be visualized in figure 9. For example, if the gross wind energy penetration reaches 65%, there would be 0.75% of surplus wind energy which equates to only 0.5% of surplus energy as a percentage of the total load. Therefore, the net wind penetration would be 64.5%. Likewise, if wind energy generates electricity equivalent to 100% of the NE load, 14.3% would be rejected and therefore while the gross wind penetration is 100%, the net wind penetration would only be 85.7%.

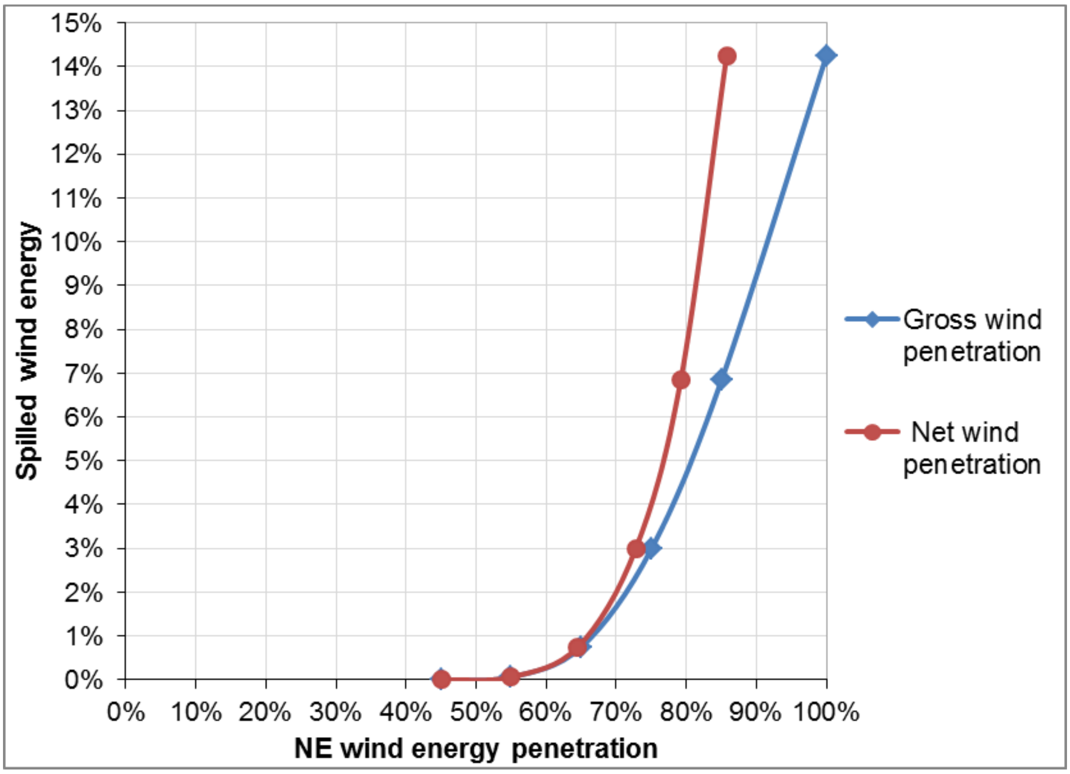

Figure 9: Gross and net wind power penetrations for increasing amounts of spilled wind energy in Brazil’s NE.

The net LCOE of wind energy increases inversely to the amount of generated wind energy less the curtailed amount. Considering the LCOE data shown in figure 2, if 33% of wind energy is curtailed from the Brotas de Macaúbas wind farms, then the net LCOE from these wind farms would increase by approximately 50% to $62/MWh (excluding externalities). This cost is comparable to the LCOE from the Parnaíba gas power plant (excluding externalities). Therefore, wind energy only becomes more expensive than gas power if less than 67% of generated wind energy is finally utilised.

There are a number of ways that significant amounts of surplus wind energy could be utilised avoiding curtailment and loss of revenue. To a degree, excess wind energy from the NE subsystem could be *exported* to other Brazilian subsystems, because all 4 subsystems in the national power systems are interlinked. Currently the transmission limits for electricity *exports* from the NE subsystem to the Southeast and North regions are 4000MW and 4400MW, respectively [49] and transmission lines interconnecting the NE subsystem with these other Brazilian subsystems are being upgraded to allow for increases in *exported* energy. Nevertheless, if large amounts of excess wind energy need to be exported to the far ends of other Brazilian regions then significant transmission line losses would be incurred.

Surplus energy from wind farms could also be stored in pumped hydro reservoirs. However, to date, none of the hydroelectric plants installed in the NE region have been adapted to operate as pumped hydro plants. Hydrogen storage is another technology which could benefit the integration of variable renewables, however, it is expensive and the round-trip efficiency is currently less than 50% [38]. Alternatively, demand-side management could utilise surplus wind energy during low demand periods, as well as reduce demand during peak demand periods. For example, Batas Bjelić et al [50] found that load flexibility via demand side response, using controllable electric sanitary hot water systems, could lower excess electricity production. (Given that the majority of residential hot water in Brazil is produced from electricity, this type of scheme could prove very effective, particularly where solar hot water installations are not possible). The economic viability of each of these methods is dependent on many factors including the amount of surplus wind energy involved. The lifetime cost of utilising this surplus energy via these 3 methods needs to be compared to the cost of curtailing the wind energy and will be the subject of future research.

The monthly and annual wind power capacity factors are also shown in table 2. The annual wind power capacity factor used in the simulation of Brazil’s NE subsystem of 40.1% was calculated from the 2013 Brennand Energia and the ONS actual generation data. Furthermore, it was calculated that the overall hourly capacity factor only drops below 10% for less than 3% of the time (considering all the 8760 hours in the entire year) and drops below 20% for approximately 11% of the time. Nevertheless, even during these hours of low wind power output, it is expected that the variations in the net load can be balanced by the large amount of hydroelectric capacity operating in the NE region.

Additionally from this generation data, the annual wind power capacity factors in 2013 for the states of Bahia, Ceará and Rio Grande do Norte were calculated to be 44.7%, 39.9% and 35.4%, respectively. The figure for Rio Grande do Norte is less than the ONS [43, 44] provisional capacity factor figure of 38%. This discrepancy is expected because, for some of the older wind farms in Rio Grande do Norte from which generation data was obtained, the provisional capacity factors in the power purchase agreements were overestimated. Nevertheless, in 2014, the 6 case study wind farms in Bahia (which were built more recently) operated with an average capacity factor of 49% and the average capacity factor for all the NE subsystem wind farms was 41% [45]. In comparison, the average capacity factor of wind farms in Brazil's southernmost state of Rio Grande do Sul was only 32.8% for the same 12 month period [45]. Furthermore, the projected capacity factors for newly contracted wind farms in the NE region are approximately 46-47% and for wind farms contracted in Piauí the figure is above 50% [18]. This indicates a trend that wind farm capacity factors are gradually increasing due to advances in wind turbine and blade technologies and because wind turbines are being installed at ever increasing altitudes [4]. The annual capacity factors of onshore wind farms in the Brazilian NE region are comparable to those in New Zealand [22] and are typically higher than in other regions of the world, even when compared to offshore wind farms in the Netherlands which, in 2012-2013, had an average capacity factor of 39% [51]. However, as the best locations for onshore wind farms in the Brazilian NE become saturated, capacity factors of newly proposed onshore wind farms in the region will in due course reach an upper limit.

The large majority of installed wind power capacity in Latin America is located in the Brazilian NE region and Brazil now ranks in the top 10 countries in terms of total installed capacity [3]. Remarkably, in 2013 wind power was even omitted from one of Brazil's national energy auctions because it was cheaper than almost all other generation sources [52]. Due to the excellent wind energy capacity factors present in various locations in the NE region, Brazil has some of the cheapest wind power in the world. At the Brazilian energy auctions held in November 2014 and August 2015 wind power in Bahia, Ceará, Piauí and Rio Grande do Norte was contracted for less than $53/MWh for a period of 20 years [18].

4.4. Gross Wind Power Penetration Forecast for the Brazilian NE Subsystem

Putting the above results in terms of real numbers, it is estimated that the annual average electricity load in Bahia will grow to approximately 4236MW by 2020. If all the planned wind farms in Bahia are commissioned on schedule by 2020, then the total installed capacity of wind power in the state will have grown to 4744MW. Therefore, using the capacity factor (already calculated in section 4.3) of 44.7%, it is expected that wind power will generate approximately 50% of the state's annual average electricity demand.

The total wind power capacity planned for installation by 2020 in Ceará and Rio Grande do Norte significantly exceeds the maximum penetration limits considering each state's individual average electricity demand. Surplus wind energy from Rio Grande do Norte is already supplying other states because the maximum wind power penetration limit of 63% calculated for that state has already been exceeded. The average electricity demand in Rio Grande do Norte is projected to grow to 1008MW [13, 42], whereas average wind power in the state is expected to reach 2005MW by 2020 (from a planned 5663MW of wind power capacity). This corresponds to a growth in gross wind power penetration (which is currently 100%) to almost 200% and therefore, by 2020, at least 50% of the state's wind power will be *exported* to other states in order to avoid curtailment.

Table 3 shows the wind power capacity currently installed, under construction, planned for construction and the total capacity expected to be operational by 2020 for each state in the Brazilian NE subsystem (that is, for each state in the NE region (excluding Maranhão)[10]. Additionally, considering the 2020 scenario for each state, the average electricity demand, the annual average wind energy generated and the wind power gross penetration have been estimated.

Table 3: Operational wind power capacity in the Brazilian NE subsystem by 2020 (Sources: ANEEL [8]; ONS [42]; ONS [13] and CCEE [18]) and corresponding gross wind power penetration.[11]

Wind Power Capacity by state					**Annual Average Wind Penetration by state**			
	Installed & Operational (MW)	Under Construction (MW)	Planned for Construction (MW)	**Total by 2020** (MW)	Assumed Capacity Factor	**Ave. Wind Power** (MW)	**2020 Ave. Demand** (MW)	**Ave. Wind Penetration by 2020**
Bahia	959	1014	2770	4744	45%	2119	4236	50.0%
Ceará	1233	241	1550	3024	40%	1207	1751	68.9%
Rio G. d. Norte	2243	598	2822	5663	35%	2005	1008	198.9%
Alagoas	0	0	0	0		0	831	0.0%
Paraíba	69	0	90	159	30%	47	823	5.7%
Pernambuco	107	272	538	917	47%	431	2332	18.5%
Piauí	264	360	1238	1862	51%	950	640	148.6%
Sergipe	35	0	0	35	30%	11	627	1.7%
NE Total	**4909**	**2485**	**9008**	**16403**		**6770**	**12248**	**55.3%**

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[10] Maranhão is excluded from the analysis because the ONS does not include this state in the Brazilian Northeast subsystem.

[11] An updated version of table 3 is shown in figure A2 of appendix A.

It is estimated that the average electricity demand for the entire NE subsystem will reach $12250MW_{avg}$ by 2020 [13]. Considering all the wind farms in the entire NE subsystem already contracted for operation by 2020, installed wind power capacity will grow to at least 16,400MW and it is estimated that annual average wind power generation will grow to more than 6700MW. Therefore wind power could generate approximately 55% of the NE subsystem's annual electricity demand by 2020, provided that all wind energy generated is actually utilised to supply the NE's electricity load and not curtailed.

In Figure 10 the expected growth in wind power capacity from 2020 is projected until 2030 for 5 states within the NE region. Given that before 2010 there was a negligible amount of installed wind power capacity in the NE, it is assumed that the installed wind power in the NE subsystem by 2030, will roughly double the 2020 capacity. Additionally, in figure 10, the gross wind energy penetration in the NE subsystem is projected until 2030. Growth in demand was assumed to be 4% from 2020-2030. It should be noted that increases in electricity demand during the next decade are difficult to accurately forecast because they are susceptible to economic growth, population growth, energy efficiency gains and electricity prices.

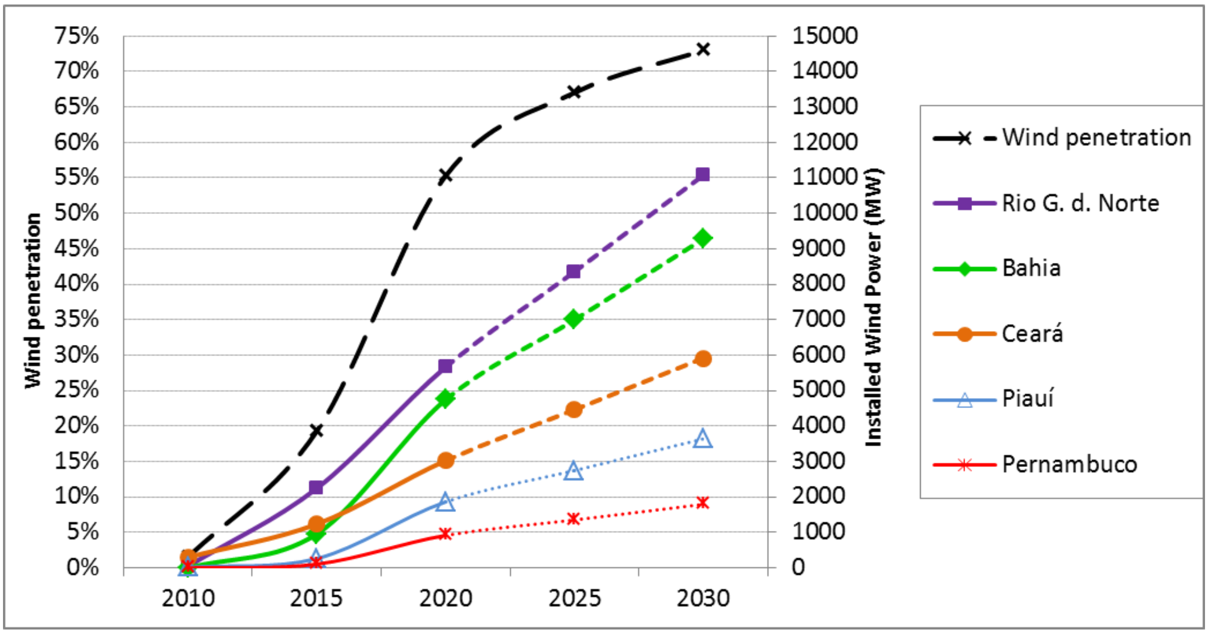

Figure 10: Wind energy penetration in the NE subsystem and installed wind power capacity for 5 different states in the NE region.

Therefore, beyond 2020 there is a large amount of uncertainty in the expected annual growth in demand, as well as the growth in wind farm deployment. Nevertheless, a total installed capacity of 32GW of wind power in the NE is quite feasible by 2030. This would see the gross wind energy penetration in the NE subsystem grow to approximately 67% by 2025 and 70-75% by 2030. Extrapolating the wind power capacity expected to be installed in each state by 2020, it was assumed that in 2025 and 2030 the states of Bahia, Ceará and Rio Grande do Norte would still account for more than 80% of the NE subsystem's total wind power capacity.

4.5. Levelised Cost of Electricity (LCOE) in the Brazilian NE Subsystem

The LCOE in the Brazilian Northeast subsystem was first calculated considering the 2014 electricity demand. The year 2014 was specifically chosen as a baseline because the proportion of hydroelectricity generation was substantially below average due to drought, however in future years this baseline is increasingly likely to become the norm. The LCOE was then calculated for four other scenarios considering the NE subsystem's electricity demand predicted for 2020 (which will reach an average of 12250MW_{avg}). For all scenarios the LCOE is calculated including and excluding social and environmental externalities. *"Imports"* denotes electricity *imported* from other Brazilian regions such as the Southeast/Central-west and North subsystems. The cost due to extensive transmission line and their respective losses is only considered for electricity *imported* from other Brazilian regions.

In the baseline scenario shown in table 4, the LCOE was calculated according to the actual demand and generation proportions for 2014. It can be observed that approximately 43% of the Brazilian NE's electricity demand was generated from thermal power sources (including 40% generated locally within the NE and approximately 3% *imported* thermal power generation from other Brazilian regions).

Table 4: LCOE (in US$) for the Northeast subsystem in 2014 by electricity generation source.

Current generation matrix in the Northeast (2014 baseline)	**2014 generation by source**		**LCOE without externalities**	**LCOE with externalities**	**Annual Emissions**
	GWh/yr	%	$/MWh	$/MWh	million tCO_{2eq}
Wind	5379	6.4%	35.07	36.24	0.06
Thermal (20% biomass, 40% gas & 40% oil/coal)	33825	40.1%	63.05	95.68	20.14
Hydroelectricity	32913	39.1%	27.31	*28.33*	1.09
Imports (80% hydro, 20% thermal)	12140	14.4%	*45.38*	*52.46*	1.70
Total	84257	100.0%	**44.76**	**59.35**	**22.99**
Current Cost of Electricity in the Northeast	**$ millions/year**		**3770.94**	**5000.54**	

In the first 2020 scenario shown in table 5, the LCOE was calculated considering no new wind power (or other renewable energy) development and the same severe drought conditions as in 2014. That is, wind power, hydroelectricity and *imported* generation were the same amounts as in 2014 and the shortfall was made up by extra thermal power generation. This scenario sees a significant increase in the proportion of thermal power compared to the 2014 baseline, because the extra load in 2020 is entirely satisfied by thermal power sources. Specifically, as much as 55% of NE's electricity demand would be supplied by thermal power (including 53% generated locally and approximately 2% *imported* thermal power generation).

Table 5: LCOE for the Northeast subsystem in 2020 with no new wind power and under drought conditions.

Current generation matrix in the Northeast (2020 with no new wind power)	**2020 generation by source**		**LCOE without externalities**	**LCOE with externalities**	**Annual Emissions**
	GWh/yr	%	$/MWh	$/MWh	million tCO_{2eq}
Wind	5379	5.0%	35.07	36.24	0.06
Thermal (20% biomass, 40% gas & 40% oil/coal)	56862	53.0%	63.05	95.68	33.86
Hydroelectricity	32913	30.7%	27.31	*28.33*	1.09
Imports (80% hydro, 20% thermal)	12140	11.3%	*45.38*	*52.46*	1.70
Total	107295	100.0%	**48.68**	**67.15**	**36.70**
Current Cost of Electricity in the Northeast	**$ millions/year**		**5223.36**	**7204.72**	

In the second 2020 scenario shown in table 6 the LCOE was calculated for a generation matrix in which wind power replaces all fossil fuel generators supplying the same 2020 NE subsystem load. Specifically, wind power generation was limited to 55% as per the penetration expected in 2020. However, hydroelectricity and *imported* hydro generation were limited to the same amounts that these sources generated in 2014 and the remaining demand was satisfied by biomass generation.

Table 6: LCOE for the Northeast subsystem in 2020 with wind power, regional and *imported* hydroelectricity (under drought conditions) and local biomass generation.

Generation matrix where wind power replaces fossil fuel sources	**2020 generation by source**		**LCOE without externalities**	**LCOE with externalities**	**Annual Emissions**
	GWh/yr	%	$/MWh	$/MWh	million tCO_{2eq}
Wind	59304	55.3%	35.07	36.24	0.71
Hydroelectricity	32913	30.7%	27.31	28.33	1.09
Thermal (100% biomass)	5364	5.0%	61.71	76.82	0.20
Imports (100% hydro)	9712	9.1%	*38.87*	*39.89*	0.32
Total	107295	100.0%	**34.36**	**36.17**	**2.32**
Cost of Electricity in the Northeast	**$ millions/year**		**3687.09**	**3881.03**	

In the third 2020 scenario shown in table 7, the LCOE was calculated for a generation matrix in which the maximum viable net penetration of 64.5% of wind power supplies the same 2020 NE subsystem load. In this scenario there is enough wind power to replace all thermal power sources (including all fossil fuel and biomass plants). The balance would be supplied entirely by hydroelectricity, however under the 2014 drought conditions about 4.8% of demand would need to be supplied by *imported* hydro.

Table 7: LCOE for the Northeast subsystem in 2020 with maximum wind power and hydroelectricity (under drought conditions).

Generation matrix where wind power replaces all thermal sources	**2020 generation by source**		**LCOE without externalities**	**LCOE with externalities**	**Annual Emissions**
	GWh/yr	%	$/MWh	$/MWh	million tCO_{2eq}
Wind	69216	64.5%	35.07	36.24	0.83
Hydroelectricity	32913	30.7%	27.31	28.33	1.09
Imports (Hydro only)	5166	4.8%	*38.87*	*39.89*	0.17
Total	107295	100.0%	**32.87**	**33.99**	**2.09**
Cost of Electricity in the Northeast	**$ millions/year**		**3526.89**	**3646.70**	

In the fourth 2020 scenario shown in table 8, the LCOE was calculated for a generation matrix supplying the same 2020 NE subsystem load assuming that hydroelectricity generation is equivalent to the average hydroelectric production during non-drought years. The average hydroelectric production during non-drought years was calculated from the hydroelectricity generated in the NE subsystem from 2005-2012 [13]. It can be observed that approximately 48% of the 2020 load could be supplied by local hydroelectric generation under non-drought conditions. Wind power generation was limited to less than 55%, as per the expected penetration for 2020, but this would be more than sufficient to avoid the need for *imported* electricity from other Brazilian regions.

Table 8: LCOE for the Northeast subsystem in 2020 with wind power and hydroelectric generation under non-drought conditions.

Generation matrix where wind power replaces thermal and imports	**2020 generation by source**		**LCOE without externalities**	**LCOE with externalities**	**Annual Emissions**
	GWh/yr	%	$/MWh	$/MWh	million tCO_{2eq}
Wind	56120	52.3%	35.07	36.24	0.67
Hydroelectricity	51175	47.7%	27.31	28.33	1.69
Total	107295	100.0%	**31.37**	**32.47**	**2.36**
Cost of Electricity in the Northeast	**$ millions/year**		**3365.52**	**3483.41**	

In each of the four scenarios the total annual cost of electricity in the NE subsystem is also calculated including and excluding social and environmental externality costs. In the second scenario, where all fossil fuel generators are replaced by wind power, the annual cost of generating electricity (including externalities) in the NE subsystem is reduced from $7.2 billion (in the first scenario) to $3.9 billion. This scenario would require an overall wind power penetration in the NE subsystem of 55% which is equivalent to the gross wind penetration projected for 2020.

In the third scenario where all thermal electricity generation (both local and *imported*) is replaced by wind power, the annual cost of generating electricity (including externalities) in the NE subsystem could be reduced from $7.2 billion (in the first scenario) to $3.6 billion or by approximately 49%. However to achieve this, a net wind energy penetration of 64.5% would be required and such a high wind penetration would likely incur additional transmission and operational costs to enable interstate balancing area cooperation which would be required to minimise curtailed energy.

In the fourth scenario where all thermal power generation is replaced by wind power and local hydroelectricity under non-drought conditions, the annual cost of generating electricity (including externalities) in the NE subsystem is reduced from $7.2 billion (in the first scenario) to $3.5 billion or by approximately 52%. This scenario has the lowest annual cost of generating electricity of all the scenarios analysed. It should be noted that under this scenario, the entire 2020 NE subsystem load would be supplied by only wind power and local hydroelectricity (under non-drought conditions). But for this to become a reality, approximately 95% of all wind farms (and their respective transmission lines) currently contracted for installation in the NE subsystem by 2019, would need to be completed and operational by 2020.

4.6. Environmental concerns and barriers to wind power

It can be observed from table 4, that CO_{2eq} emissions as a result of electricity generation in the Brazilian NE subsystem totalled approximately 23 million tonnes in 2014. In the first 2020 scenario with no new wind power and hydroelectricity under drought conditions, the total CO_{2eq} emissions would increase to approximately 37 million tonnes annually based on the NE subsystem’s expected 2020 electricity demand. Moreover, the generation mix in this scenario would have an overall emissions factor of 342kg of CO_{2eq} per MWh. Considering the second, third and fourth 2020 scenarios, shown in tables 6, 7 and 8 in which wind power replaces all fossil fuel electricity generation, CO_{2eq} emissions would be reduced to less than 2.4 million tonnes per year based on the NE subsystem's expected 2020 electricity demand. Furthermore, the overall emissions factor in the second, third and fourth scenarios would only be approximately 19-22kg of CO_{2eq} per MWh. Despite these potential environmental gains, there are environmental concerns about large scale wind power development.

One of the greatest barriers to the development of renewable energy technologies such as wind power is their elevated initial cost compared to conventional sources. Additionally, traditional forms of cost evaluation don't consider the environmental costs of conventional energy sources [36] and often don't consider the lifetime costs of fuel, operations and maintenance of equipment and transmission systems of traditional generation technologies [1]. There is also prejudice against wind power development, from conservative lobby groups, government and the media [53]. Proposed wind farm projects in Australia, the UK and the USA are often not approved by local municipalities because of fears from local residents of the aesthetic impact of wind turbines on the local landscape [54]. Residents and landowners lobby to stop construction of wind farms because of their visual impact and claim that noise from wind farms causes health problems despite the fact that there is no scientific evidence for this [55, 56].

5. CONCLUSION

It is estimated that the average electricity demand for the entire Brazilian NE subsystem will grow to $12250MW_{avg}$ by 2020 [13]. Until 2012 hydroelectric generation typically contributed more than 70% of the total electricity demand, however, given the limited water resources in the region, there is no possibility to build new large scale hydroelectric plants. On the other hand, the total average wind power generated from wind farms in the NE subsystem is projected to grow to more than $6700MW_{avg}$ by 2020. Considering all the wind farms in the NE subsystem expected to be operational by 2020, it is estimated that wind power will generate approximately 55% of the NE's annual electricity demand by 2020. This could reduce the need for electricity generation from fossil fuel sources in the NE subsystem to zero, even under severe drought conditions.

It was argued that the NE subsystem could be 100% flexible to follow the net load curve given the enormous hydroelectric capacity already existing in the NE region. Thus, allowing for up to 1% of wind energy to be curtailed or *exported* to other Brazilian subsystems, the viable maximum wind energy penetration in the NE subsystem was estimated to be 65%. This high wind energy penetration is feasible in the Brazilian NE due to the excellent capacity factors of wind farms in the region and because the average diurnal wind power output closely correlates with the NE hourly load. Considering the NE's expected load for 2020, the remaining 35% of electricity generation could be satisfied entirely from hydroelectricity, and even under drought conditions, only 5% *imported* hydro would be required from neighbouring subsystems.

In 2014 approximately 43% of the Brazilian NE's electricity demand was generated from thermal power sources. Considering the first 2020 scenario of drought conditions with no new wind power where as much as 55% of NE's electricity demand is supplied by thermal power sources, then in this worst case scenario, the NE's total electricity generation cost (including externalities) would reach approximately $7.2 billion by 2020. However, it is estimated that by 2020, wind power will generate approximately 55% of the NE subsystem's annual electricity demand. In this 2020 scenario hydroelectricity (regional and *imported*) under drought conditions would still supply 40% of demand and biomass sources could supply the remaining 5%. Therefore, the NE subsystem demand could be supplied by a 100% renewable generation matrix. This could reduce the overall cost of electricity generation in the NE subsystem by $3.3 billion (46%) and reduce CO_{2eq} emissions by approximately 34 million tonnes per year compared to the worst case scenario.

Assuming that the majority of contracted wind farms are commissioned on schedule, wind power penetration will exceed 50% in Brazil's NE subsystem by the end of the decade. Nevertheless, for this to be realized, the region's transmission infrastructure will need to be sufficiently upgraded to allow for interstate balancing in order to avoid curtailment of excess wind energy. Future work will include a more detailed evaluation of the overall levelised cost of integrating a 100% renewable generation matrix in the NE region including the cost of additional transmission infrastructure.

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7. REFERENCES

[1] de Jong P, Kiperstok A, Torres E A. Economic and environmental analysis of electricity generation technologies in Brazil. Renewable and Sustainable Energy Reviews 2015; 52: 725–739.

[2] Schubert C. Atlas Eolico: Bahia. SECTI, SEINFRA, CIMATEC/ SENAI, Salvador, 2013.

[3] GWEC - Global Wind Energy Council. Global Wind Report Annual Market Update 2014, 2015.

[4] REN21 - Renewable Energy Policy Network for the 21st Century. Renewables 2015 Global Status Report. Paris; 2015. Available at: http://www.ren21.net/status-of-renewables/global-status-report/ accessed on 25/08/2015.

[5] Shafiullah GM, Oo A M T, Jarvis D, Shawkat Ali A B M, Wolfs P. Potential Challenges: Integrating Renewable Energy with the Smart Grid. AUPEC 2010 - 20th Australasian Universities Power Engineering Conference: "Power Quality for the 21st Century". IEEE Computer Society, 2010.

[6] Hossain M J, Pota, H R, Mahmud, M A, Ramos, R A. Investigation of the impacts of large-scale wind power penetration on the angle and voltage stability of power systems. IEEE Systems Journal; (2012), 6 (1), art. no. 6026894, pp. 76-84.

[7] Vilchez E, Stenzel J. Impact of renewable energy generation technologies on the power quality of the electrical power systems. 22nd International Conference on Electricity Distribution. Institution of Engineering and Technology, 2013.

[8] ANEEL – Agência Nacional da Energia Elétrica / Brazilian National Electricity Agency, BIG – Banco de Informações de Geração / Information Bank of Generation; 2015. Available at: http://www.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.asp accessed on 26/08/2015.

[9] Martins F R, Pereira E B. Enhancing information for solar and wind energy technology deployment in Brazil. Energy Policy 2011; 39: 4378–4390.

[10] Fearnside P M, Pueyo S. Greenhouse-gas emissions from tropical dams. Nature Climate Change 2012; 2: 382–384. Available at: http://dx.doi.org/10.1038/nclimate1540 accessed on 28/05/2015.

[11] Marengo J A. Water and Climate Change. Estudos avançados 2008; 22: 63.

[12] de Jong P, Sánchez A S, Esquerre K, Kalid R A, Torres E A. Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the Northeast region of Brazil. Renewable and Sustainable Energy Reviews 2013; 23: 526–535.

[13] ONS – Operador Nacional do Sistema Elétrico. Históricas da Operação - Geração de Energia; 2014a. Available at: http://www.ons.org.br/historico/geracao_energia.aspx Accessed on 16/01/2015.

[14] Ulbig A, Andersson G. Analyzing operational flexibility of electric power systems. Electrical Power and Energy Systems 2015; 72: 155–164.

[15] Scorah H, Sopinka A, Van Kooten G C. The economics of storage, transmission and drought: integrating variable wind power into spatially separated electricity grids. Energy Economics 2012; 34: 536–541.

[16] Marengo J A, Chou S C, Kay G, Alves L M, Pesquero J F, Soares W R, et al. Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. Climate Dynamics 2012; 38: 1829–1848.

[17] Lucena A F P, Szklo A S, Schaeffer R, Souza R R De, Borba B S M C, Costa I V L Da, Júnior A O P, Cunha S H F da, The vulnerability of renewable energy to climate change in Brazil. Energy Policy 2009; 37: 879-889.

[18] CCEE - Câmara de Comercialização de Energia Elétrica / Brazilian Chamber of Electricity Trading. Info leilão. 2013/2014/2015. Available at: www.ccee.org.br accessed on 06/09/2015.

[19] Mai T, Wiser R, Sandor D, Brinkman G, Heath G, Denholm P, Hostick D J, Darghouth N, Schlosser A, Strzepek K. Exploration of High-Penetration Renewable Electricity Futures. Vol. 1 of Renewable Electricity Futures Study. NREL/TP-6A20-52409-1. Golden, CO: National Renewable Energy Laboratory. (2012).

[20] Elliston B, Macgill I, Diesendorf M. Least cost 100% renewable electricity scenarios in the Australian National Electricity Market. Energy Policy 2013; 59: 270–282.

[21] Elliston B, Diesendorf M, Macgill I. Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market. Energy Policy 2012; 45: 606–613.

[22] Mason I G, Page S C, Williamson A G. A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources. Energy Policy 2010; 38: 3973–3984.

[23] Mason I G, Page S C, Williamson A G. Security of supply, energy spillage control and peaking options within a 100% renewable electricity system for New Zealand. Energy Policy 2013; 60: 324–333.

[24] Purvins A, Papaioannou I T, Oleinikova I, Tzimas E. Effects of variable renewable power on a country-scale electricity system: High penetration of hydro power plants and wind farms in electricity generation. Energy 2012; 43: 225–236.

[25] Eichman J D, Mueller F, Tarroja B, Schell L S, Samuelsen S. Exploration of the integration of renewable resources into California's electric system using the Holistic Grid Resource Integration and Deployment (HiGRID) tool. Energy 2013; 50: 353–363.

[26] Pete C M, Acker T L, Jordan G, Harpman D A. Western wind and solar integration study hydropower analysis: Benefits of hydropower in large-scale integration of renewables in the Western United States. Proceedings of ASME 2010 4th International Conference on Energy Sustainability; 2010.

[27] Nikolakakis T, Fthenakis V. The optimum mix of electricity from wind- and solar-sources in conventional power systems: Evaluating the case for New York State. Energy Policy 2011; 39: 6972–6980.

[28] GE Energy. Western Wind and Solar Integration Study. The National Renewable Energy Laboratory – NREL; 2010.

[29] Moura P S, Almeida A T de. Multi-objective optimization of a mixed renewable system with demand-side management. Renewable and Sustainable Energy Reviews 2010; 14: 1461–1468.

[30] Denholm P, Margolis R M. Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. Energy Policy 2007; 35: 2852–2861.

[31] De Jonghe C, Delarue E, Belmans R, D'haeseleer W. Determining optimal electricity technology mix with high level of wind power penetration. Applied Energy 2011; 88: 2231–2238.

[32] Borba B S M C, Szklo A, Schaeffer R. Plug-in hybrid electric vehicles as a way to maximize the integration of variable renewable energy in power systems: The case of wind generation in northeastern Brazil. Energy 2012; 37: 469-481.

[33] Bezerra B, Barroso L A, Brito M, Porrua F, Flach B, Pereira M V. Measuring the Hydroelectric Regularization Capacity of the Brazilian Hydrothermal System, IEEE; 2010.

[34] Gárdos I, Furst R D, Gomes P, Bianco A. Large scale integration of renewable sources in the Brazilian bulk power system. Operador Nacional do Sistema Elétrico – ONS, Brazil. CIGRE; 2010.

[35] Pereira Jr A O, Costa R C, Costa C V, Marreco J M, Rovere E L. Perspectives for the expansion of new renewable energy sources in Brazil. Renewable and Sustainable Energy Reviews 2013; 23: 49-59.

[36] NEA-Nuclear Energy Agency/IEA-International Energy Agency/OECD-Organisation for Economic Cooperation and Development. Projected Costs of Generating Electricity; 2010 Edition.

[37] de Jong P, Kiperstok A, Torres E A. Integration of Variable Renewable Energy into the Electricity Grid in Bahia Brazil. In: Eficiência Energética e Produção de Energia Renovável Políticas, oportunidades e desafios para o mercado, para a ciência e para a educação. Guerra J B S O A, Leal W, Dutra L, Ladwig N I, Costa R S, editors. Florianópolis: Consórcio Projeto REGSA, 2014. pp. 259-278.

[38] Lund P D, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews 2015; 45: 785–807.

[39] Acker T L, Robitaille A, Holttinen H, Piekutowski M, John Olav Giæver Tande J O G. Integration of wind and hydropower systems: Results of IEA wind task 24. Wind Engineering 2012; v 36, n 1, p 1-18.

[40] Porrua F, Chabar R, Thomé L M, Barroso L A, Pereira M. Incorporating Large-Scale Renewable to the Transmission Grid: Technical and Regulatory Issues. IEEE; 2009.

[41] Fleury Á, Arteiro F, Brasil D, Gomes P, Franceschi A. Integration of Wind Power Plants into the Electric System - The Brazilian Experience. Proceedings of the 2012 6th IEEE/PES Transmission and Distribution: Latin America Conference and Exposition, T and D-LA 2012.

[42] ONS – Operador Nacional do Sistema Elétrico / Brazilian National Electricity System Operator. RE-3-128-2008 PEL 2009-2010; 2008.

[43] ONS – Operador Nacional do Sistema Elétrico, Acompanhamento mensal de geração de energia das usinas eolielétricas com programação e despacho centralizados pelo ONS; July, 2013a. Available at: http://www.ons.org.br/download/resultados_operacao/boletim_mensal_geracao_eolica/Boletim_Eolica_jul-2013.pdf accessed on 24/09/2013.

[44] ONS – Operador Nacional do Sistema Elétrico, Acompanhamento mensal de geração de energia das usinas eolielétricas com programação e despacho centralizados pelo ONS; September, 2013b. Available at: http://www.ons.org.br/download/resultados_operacao/boletim_mensal_geracao_eolica/Boletim_Eolica_set-2013.pdf accessed on 06/11/2013.

[45] ONS – Operador Nacional do Sistema Elétrico, Boletim Mensal de Geração Eólica - Janeiro/ Fevereiro / Março / Abril / Maio / Junho / Julho / Agosto / Setembro / Outubro / Novembro / Dezembro, 2014; 2014b. Available at: http://www.ons.org.br/resultados_operacao/boletim_mensal_geracao_eolica/index.aspx accessed on 16/07/2015.

[46] Elliston B, Macgill I, Diesendorf M. Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market. Renewable Energy 2014; 66: 196–204.

[47] Sinden G. Characteristics of UK wind resource: Long-term patterns and relationship to electricity demand. Energy Policy 2007; 35: 112–127.

[48] Hoicka C E, Rowlands I H. Solar and wind resource complementarity: Advancing options for renewable electricity integration in Ontario, Canada. Renewable Energy 2011; 36: 97-107.

[49] ONS – Operador Nacional do Sistema Elétrico / Brazilian National Electricity System: Apresentações Programa Mensal da Operação Energética (PMO). PMO de setembro de 2015 - Nota Executiva GPO/GPO2/129/2015; 2015a. Available at: http://www.ons.org.br/operacao/apresentacoesPMO.aspx accessed on 16/09/2015.

[50] Batas Bjelić I, Rajaković N, Ćosić B, Duić N. Increasing wind power penetration into the existing Serbian energy system. Energy 2013; 57: 30–37.

[51] IEA - International Energy Agency. IEA Wind 2014 Annual Report - Executive Committee of the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems of the International Energy Agency. IEA Wind; August 2015. Available at: https://www.ieawind.org/annual_reports_PDF/2014/2014%20AR_smallfile.pdf Accessed on 20/12/2015

[52] REN21 - Renewable Energy Policy Network for the 21st Century. Renewables 2014 Global Status Report. Paris; 2014. Available at: http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_full%20report_low%20res.pdf accessed on 11/05/2015.

[53] Goldenberg S. Media campaign against windfarms funded by anonymous conservatives. The Guardian; 2013. Available at: http://www.guardian.co.uk/environment/2013/feb/15/media-campaign-windfarms-conservatives Accessed on 18/02/2013.

[54] Bella D, Gray T, Haggett C, Swaffield J. Re-visiting the 'social gap': public opinion and relations of power in the local politics of wind energy. Environmental Politics 2013; 22 (1): 115-135.

[55] Seccombe M. A Field Guide To The War On Wind Power. Global Mail; 2012. Available at: http://www.theglobalmail.org/feature/a-field-guide-to-the-war-on-wind-power/406/ accessed on 18/02/2013.

[56] SONUS Pty Ltd. Wind Farm Technical Paper - Environmental Noise. Prepared for Clean Energy Council (Australia); November 2010.

[57] ONS – Operador Nacional do Sistema Elétrico. 2ª Revisão Quadrimestral das Projeções da demanda de energia elétrica do Sistema Interligado Nacional 2015-2019. EPE - Empresa Pesquisa Energética/ONS; 2015b.

CHAPTER 4

Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid

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Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid

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ABSTRACT

This study examines the optimal integration of high proportions of wind energy into an electricity grid which traditionally depends on hydroelectricity. Wind power in the Brazilian Northeast (NE) is expected to generate 57% of the NE's electricity supply by 2020. As rainfall in the NE region is susceptible to climate change, it is anticipated that wind energy could substitute lost hydroelectric availability. The Weather Research and Forecasting (WRF) Model is used to simulate wind speeds for all of 2014 and calculate wind power across the entire NE region of Brazil. The NE region's aggregate hourly wind generation and net load curve are then estimated for increasing wind penetrations using the planned rollout of wind farms in the region as a baseline. The maximum wind energy penetration in the region is estimated to be approximately 50% before significant amounts of energy would need to be curtailed or exported to other Brazilian regions. It was found that wind energy generation from coastal wind farms in the region best correlates with the hourly and monthly variations of the NE subsystem's load curve. Conversely, inland wind farms on the NE's elevated plateaus typically generate more power late at night, but have higher capacity factors.

Keywords: Wind Power; Hydroelectricity; Solar Power; Renewable Energy Integration; Forecasting; WRF.

1. INTRODUCTION

The Paris Agreement to limit the global temperature rise below 2 degrees Celsius above pre-industrial levels officially entered into force in November 2016. One aspect of combating climate change will necessitate the use of larger proportions of emissions free electricity generation such as the use of more hydroelectricity, wind and solar power. In many developing countries, hydroelectricity is still the majority source of renewable energy, however, climate change may have a negative impact on the long term of hydroelectric availability as a result of more frequent and intense climate induced droughts [1]. It is anticipated that wind energy (and also other renewables such as solar PV) could replace lost hydroelectric potential, however, unlike dispatchable hydroelectricity, wind energy is somewhat stochastic.

Wind energy penetration in terms of percentage of electricity generation is already well above 20% in several countries and balancing regions around the world. In 2015 wind energy penetration was 42% in Denmark, 35% in South Australia, 31% in Iowa, 24% in Ireland and 23% in Portugal [2, 3]. However, wind power is a variable generation technology (that is, the amount of energy production cannot be easily regulated to match demand, as it is dependent on fluctuating weather conditions). Therefore, considering the steadily increasing penetrations of wind energy expected in various countries and balancing areas, the main engineering challenge will be the smooth integration of this power source into the electricity grid. One such balancing area is the Northeast (NE) region of Brazil, where wind energy is projected to produce more than half of the NE’s electricity demand by 2020 [4]. Using the Brazilian NE region as a case study, the aim of this study is to forecast the detailed hourly, monthly and surplus wind power production using a numerical weather prediction tool and determine to what extent wind power correlates with demand and complements existing generation infrastructure. This paper takes a holistic approach to the challenges of integrating increasing penetrations of wind energy under different scenarios and also considers the impacts of global warming on various renewable energy sources. This type of study is very important for regions which expect to have substantial amounts of new wind energy, but rely heavily on hydroelectric generation (or biomass) that could be susceptible to climate change. Furthermore, a unique method is demonstrated to estimate the optimal installed wind power capacity at various wind farm locations in a balancing region that aggregately would generate electricity to best correlate with the electricity load curve.

As wind power generation is variable, system operators treat it as a negative load and hence the concept of load net wind or net load (defined as, the hourly electricity load minus hourly wind and solar power generation) is used [5, 6, 7, 8]. For example, due to diurnal and seasonal wind variability in the NE region, it was estimated that if wind power penetration increased above 65%, then at certain times (such as, during hours of low load), hourly wind power would be greater than the NE subsystem’s electricity demand [9]. Thus, at certain times the net load would become negative, which is an indication that there is surplus wind energy. This excess wind energy would need to be curtailed or if possible *exported* to other Brazilian regions [9]. At other times, when the output from wind power is low and demand is high, gap filling from dispatchable backup generators is required (for example from existing hydroelectric and gas generator capacity). Understanding the constraints and predicting the output of high proportions of wind energy is essential to ensure that grid reliability is maintained and also to prevent energy being wasted unnecessarily. For example in 2015, 15% of China’s wind energy generation had to be curtailed due to transmission difficulties [2].

While this study focusses on integrating wind energy generation in the Brazilian NE power system, the methodology could be equally applied to other regions where similar challenges exist. Furthermore, the results of this study are compared to similar studies in other regions.

1.1. Objectives

The principal objective of this study is to simulate the aggregate hourly wind power and net load in the Brazilian NE subsystem based on the planned wind farm deployment until 2020. Firstly, the locations and capacities of all wind farms contracted in the NE region and projected to be operational by 2020 are determined. The Weather Research and Forecasting (WRF) Model is used to simulate hourly wind speeds at the various wind farm locations in the NE region (for all of 2014). Then the hourly wind power is calculated (where wind farms are or will be built) using a standard power curve for typical wind turbines used in the region.

This paper is a continuation of the work by de Jong et al [9], which estimated the hourly and monthly aggregate wind power production in the Brazilian NE region by 2020, based on observed wind power generation data from 16 existing wind farms located in the states of Bahia, Rio Grande do Norte and Ceará. Rather than extrapolating observed wind power data, this paper simulates wind power generation using the WRF model, based on the planned installation of more than 600 wind farms across all 8 states in the NE subsystem. This novel method differs from previous studies that estimate wind energy production because many of them extrapolate future wind power data from a relatively small number of existing wind farms or poorly located weather stations.

In the baseline scenario, the aggregate hourly wind power and net load for the NE subsystem is calculated based on planned wind farm deployment until 2020 and beyond. Based on the hydroelectric minimum flow requirements of the NE’s São Francisco River, it was assumed that existing hydroelectric and gas generators in the NE region of Brazil have 80% scheduling flexibility to quickly modulate electricity generation to effectively supply the net load and balance the power system. In a second and third scenario it is assumed that the installed wind power capacities at all wind farm locations are entirely flexible. For the second scenario wind power capacities are optimised in order to achieve the maximum wind energy penetration in the NE subsystem with least curtailment. Thus, the locations of wind farms that generate wind power, which best correlates to the NE load curve, can be determined. In the third scenario, the wind power capacities are optimised to achieve least cost of electricity generation. Thus, the locations of the most cost effective wind farms (those with the highest capacity factors), can be determined.

Forecasting the details of future wind power production is important in a regional context because transmission systems will need to be expanded and the power system will need to be adapted in order to effectively integrate new wind farms with existing hydroelectric generation. Furthermore, existing hydroelectric generation is susceptible to droughts in the short term and climate change in the long term (see section 1.2), thus the viability of wind energy effectively replacing lost hydroelectric production needs to be investigated.

1.2. The Brazilian Northeast's electricity matrix and the impacts of climate change

In recent years, the Brazilian electricity generation matrix has been diversified and wind power has become the second cheapest generation technology (after hydroelectricity) in terms of levelised cost of electricity [10, 11].[12] In the past, Brazil heavily relied upon large scale hydroelectric plants for electricity generation, however, the large majority of hydroelectric potential in the Northeast (NE) region of Brazil is already being exploited and there is no potential for new large scale plants [12]. As a result, wind power deployment in the NE region of Brazil has grown rapidly since 2010. Currently the NE region has approximately 8250MW of wind power capacity connected to the grid and by 2020 an additional 7500MW will be installed [4]. Therefore by 2020, almost 16000MW of wind power capacity will be operational across more than 80 municipalities [4].

The interior of the NE region of Brazil is mostly semi-arid and suffers from frequent droughts, which can also affect the region's power supply. This is because the majority of the NE's electricity (typically 70%) is supplied from hydroelectric dams that are located in the lower-middle São Francisco River basin in the centre of the NE region (one of the driest areas in the country). Furthermore, low rainfall, river flows and extended drought in the Northeast region are also linked to the El Niño phenomenon [13].

From 2005 to 2007 hydro electricity was responsible for more than 87% of the NE's electricity supply [14]. However, as a result of a drought in the region that began in 2012, in 2013, 2014, 2015 and 2016 these hydroelectric plants only generated 42%, 39%, 31% and

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[12] As a result, total installed wind power capacity in Brazil already ranks amongst the top 10 countries in the world [2].

25%, respectively, of the NE subsystem's total electricity demand. The effect on hydroelectricity generation is illustrated in figure 1. Until recently this shortfall was mostly substituted by unsustainable fossil fuel power, however, in 2016 wind power generated approximately 30% of the Northeast's electricity due to the rapid growth of this technology in the region.

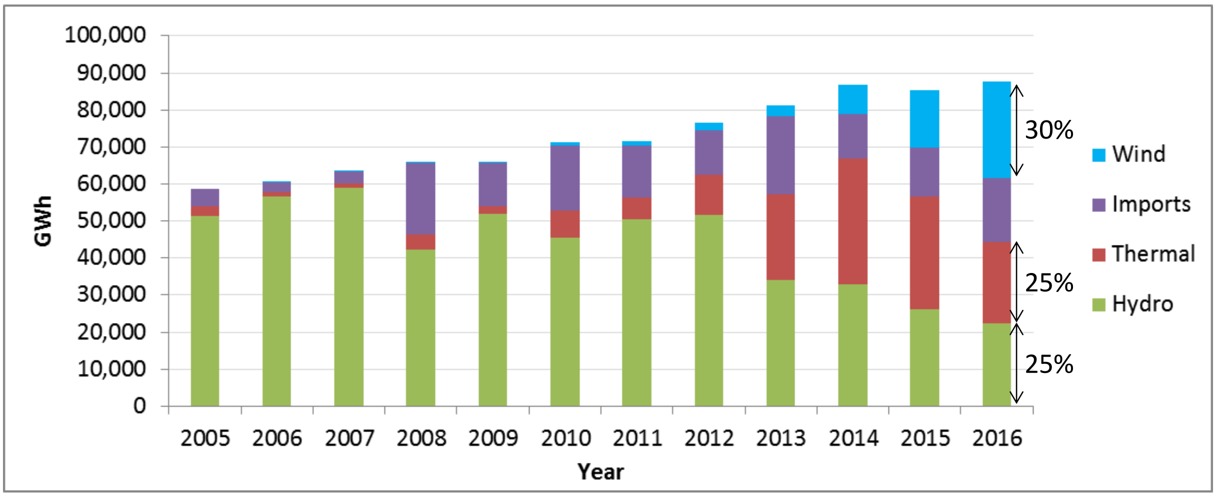

Figure 1: Sources of the Northeast's Electricity. *"Thermal"* electricity generation in the NE is from fossil fuels & biomass. *"Imports"* consists mostly of hydroelectricity *imported* from other Brazilian regions. Source: ONS [14].

In November 2015 the water level in the São Francisco basin fell to only 5% of the total capacity in terms of stored energy (its lowest level since all the dams were completed in 1994) [14, 4]. Moreover, Global Warming, which will affect the long-term temperature and rainfall patterns in the NE region, may threaten hydroelectricity production to an even greater degree. Higher temperatures and significantly reduced rainfall are predicted for the North and NE regions due to Global Warming and these climatic changes will also threaten hydroelectricity and biomass production in these regions of Brazil [13, 15, 16]. By 2100, overall annual rainfall reductions of 19% in the Amazon and 35% in São Francisco basin are predicted [17]. Therefore, both wind and solar power will need to be significantly exploited in order for the NE region to maintain its relatively low emissions factor from electricity generation.

Conversely, the decline in rainfall predicted for the NE and North regions due to climate change will also result in a significant increase in these regions' average solar radiation levels. Additionally, average wind speeds in the Brazilian North and NE are predicted to increase significantly. Considering the IPCC A2 and B2 emissions scenarios, Lucena et al [18] estimated that by 2100, wind power potential in these Brazilian regions will more than triple the 2001 baseline reference. However, it is important to note that regional climate projections are subject to various cumulative uncertainties related to the emission scenarios, climate models and downscaling methods used [18]. Furthermore, changes in vegetation cover that alters terrain roughness (for example as a result of deforestation), can also significantly affect wind speeds [18]. However terrain roughness in the NE is unlikely to be greatly impacted by climate change, as the interior plateaus in the region are typically semi-arid savanna and coastal wind farms are located on sand dunes or dry grasslands.

1.3. Wind regime in the Brazilian Northeast

Strong and consistent winds exist along the Brazilian Northeast coastline and on the inland plateaus. These are as a result of the convergence of subtropical anticyclone winds from the south Atlantic toward the equatorial depression and the constant trade winds from the east [19, 20]. Several wind farms in the Northeast are or will be built on coastal sand dunes, which typically have a low roughness, while other wind farms that are located on the higher elevations of inland plateaus, benefit from the vertical compression of airflow [20].

The majority of the wind power potential in Brazil exists in NE region [20]. Furthermore, while the Brazilian NE region exhibits consistently strong winds, strong tropical depressions and tropical cyclones do not form over the South Atlantic due to a dry middle troposphere [21]. Therefore, wind farms in the Brazilian NE are not at risk from tropical cyclones.

Schubert [19] demonstrates that the majority of wind power potential in Bahia occurs on the inland plateaus between 20:00h and 08:00h, because average wind speeds are significantly higher at night-time. As a result the diurnal average hourly wind power generation in the interior of Bahia drops to its lowest level during mid-afternoon [9, 22].

Similarly, Eichman et al [23] demonstrated that wind turbines in California produce most of their electricity during the night and therefore when combined with solar power a complementarity exists. Rife et al [24] demonstrated the existence of several recurring nocturnal low level jets in various locations, including, the Great Plains of North America, northwest China, Southeast Asia, Australia, Ethiopia, Angola, Namibia, India, Iran and Venezuela, etc. A strong recurring nocturnal low level jet can also be observed graphically in [24] over the interior highlands of the Brazilian NE that occurs in both summer and to a lesser extent in winter. This nocturnal low level jet explains the existence of a diurnal wind cycle with higher wind speeds occurring at night on the inland plateaus of Bahia. In contrast, coastal wind farms in the NE region generate most of their energy during the day [22] and therefore, complement the generation from inland wind farms in the region.

1.4. Previous studies on simulating wind speeds and wind power

There have been a few papers which model high penetrations of wind power combined with existing hydroelectric generation. Using ECMWF (European Centre for Medium- Range Weather Forecasts) data, Schmidt et al [25] found that there is a seasonal complementarity between wind power in the NE states of Bahia, Rio Grande do Norte and Ceará and the variability of hydroelectric availability in the NE, Southeast and North regions of Brazil. Wind power integration will better enable hydroelectric resources to be increasingly used for balancing of short term fluctuations of variable renewables [25]. However, the study does not assess how the electrical power system would manage the intermittency and curtailment of wind power on shorter periods of time (e.g. due to the hourly variations of wind power).

Using existing generation data, Mason et al [26] demonstrated that 100% of New Zealand's electricity generation could be securely supplied by renewable energy sources with almost negligible spilled wind energy. Their simulation took into consideration the long-term variability of hydroelectricity including drought periods and the short term (half-hourly) variability of wind power. Together these technologies accounted for 72% of the generation capacity, while the remainder was made up of geothermal, pumped hydro energy storage (or biogas) peaking plants, and biomass-fuelled generation.

There have been several other studies that simulate a regions wind speed or wind energy and compare the modelled results with observed data. For example, Carvalho et al [27, 28] evaluated the performance of the Weather Research and Forecast (WRF) model to simulate wind speed, direction and wind energy potential under different numerical and physical options for an area of Portugal. They found that the model accurately reproduced the local wind regime, however, there was a significant underestimation of wind speeds in places with high terrain complexity [27] while the latter study showed an overestimation of wind speeds at most of the measuring stations [28]. Similarly, Draxl et al [29] compare WRF model simulated wind speeds against observations, using different planetary boundary layer parameterization settings at one location in western Denmark.

Ramos et al [30] analysed wind speeds in the state of Alagoas (in the NE of Brazil) using the WRF model during a period of 1 year. Similarly Pinto et al [31] compared observed wind speed and direction data with numerical weather prediction model data from the Brazilian Regional Atmospheric Modelling System (BRAMS) at 2 locations in Alagoas. Both studies found that the weather prediction models were more reliable for sites in the interior of the state than on the coast.

Oliveira [32] used WRF and BRAMS numerical simulations to analyse the wind energy potential of the state Paraíba in the NE region of Brazil and found that the best wind energy potential occurred in the interior of the state during spring. Both numerical models showed strong correlations with observed wind speed data, but tended to show positive biases at heights above 10m. Finally, Tuchtenhagen et al [33] used the WRF model to assess the wind energy potential over all of Brazil for every hour of 2011. However, most of these numerical weather prediction based studies do not attempt to examine the impacts and limits of large scale wind power integration in a particular power system and they do not estimate the amount of wind power that may need to be curtailed or *exported* to a neighbouring power system.

Miranda et al [34] contributed more detail to the analysis of [9] by including power system flexibility constraints and transmission limits. Their model predicted that with wind power penetrations of 21% and 32% in the NE region, wind power curtailment would reach 10% and 30%, respectively. However, the model results are at odds with actual 2016 wind energy generation data from the ONS [14] which shows that wind power generated 30% of the NE’s electricity demand without wind energy curtailment or *exportation*. While the study considers transmission limits in the region it does not allow for the planned expansion of the transmission system in the scenarios with expanded wind power. Another discrepancy is that the derived wind energy reference capacity factor of 24% is far below the recorded average annual capacity factor for the NE region which is typically in excess of 40% [22]. Furthermore, the study uses wind speed data from only 8 weather stations (mostly located in urban areas) and consequently may not properly allow for the geographical dispersion of the more than 600 wind farms planned for the region.

Having a large geographical dispersion of wind farms is an important element in smoothing output. A study by the Brazilian Energy Research Organisation / Empresa de Pesquisa

Energética (EPE) [35] simulating wind power generation in the NE region showed that the percentage of extreme ramp variations, as well as the duration of very low wind power generation during wind lulls, decrease with greater geographical dispersion of wind power capacity.

Wang et al [36] demonstrate the importance of grid flexibility and improved wind power forecasting in reducing wind energy curtailment and grid operational costs by modelling 3 different power systems. Using NREL wind data, Waite and Modi [37] found that significant wind power curtailment can occur with increasing amounts of wind penetration as a result of seasonal and, to a lesser degree, diurnal mismatches between wind energy generation and electricity demand, as well as due to continuously operating baseload generation. Transmission constraints can further increase curtailment, however, this additional curtailment can largely be overcome by modest increases in specific transmission capacity [37].

Reducing or replacing baseload generation with flexible generation able to rapidly ramp supply up and down can reduce wind power curtailment, while inserting solar generation can also complement wind energy [7, 8]. Furthermore, incorporating demand response, load shifting and storage can help avoid curtailment of variable renewables [8], but the implementation of energy storage systems can entail significant costs [38]. As proposed by Zhang et al [39], an integrated planning model simultaneously incorporating generation, regulation, transmission and demand response capacities, can reduce curtailment and minimise power system costs.

It is important to note that different models and simulation tools are susceptible to their temporal resolutions and to the accuracy of the input data used [40]. For example, detailed hub height wind speed and wind power data are often not publically available [37]. Sub-hourly modelling may be beneficial in evaluating flexible resources in a power system with wind resources spread over a large geographic region, however, model assumptions, such as fuel prices, generation mix, ramp rates and demand profile are likely to have a more significant impact on total system cost results [41].

Therefore, analysis of wind integration into a power system is highly dependent on the particulars of the power system in question. Conclusions from one study on wind power cannot be automatically applied to another region or country. Rather, some of the results from other regions can be contrasted against the results of this study. For example, the integration of wind (and solar) energy in the USA is limited to approximately 30% before curtailment becomes significant because the majority of existing generators are inflexible baseload units and also because more wind energy is generated at night than during the day, as well as due to seasonal variability [7, 8, 23]. While, in this study, it will be shown that higher levels of wind penetration can be achieved in the Brazilian NE than in many other countries or regions due to the low variability of wind speeds in the region and because of the flexibility of the NE's generation matrix.

While many of the above studies estimate the amount of curtailed wind power, this paper also uses a novel method to identify the advantages and limitations of various wind farm locations with respect to the particulars of an entire balancing area (including the impacts of climate change on the region's resources). That is, the hourly and monthly wind energy generation of various wind farm locations is analysed economically and in order to identify how different groups of wind farms in a balancing region complement existing hydroelectricity and correlate to the load curve. It is the first time that this type of holistic approach has been undertaken in Brazil with this level of detail.

2. METHODOLOGY

In many regions, including the Brazilian NE, there is a lack of publically available wind power data and therefore, wind power data, commonly used in previous studies, is often limited to only a few non-proprietary locations in a specific balancing region. Furthermore, wind power data extrapolated from existing wind farm locations is not representative of generation from all wind farm locations that will exist in the future, as they will be significantly more geographically dispersed. Therefore, the originality of this study is that it uses a numerical weather prediction tool to simulate wind power integration across several geographically dispersed locations of both existing and future wind farms.

In this section the method, tools and data sources of the study are outlined. In section 2.1 the WRF numerical weather prediction model settings and boundary conditions are explained. Section 2.2 describes the details of the wind farm clusters and locations where wind speed data was simulated, as well as the wind turbine power curve used to calculate hourly wind power. In section 2.3 the simulated wind power data is compared to observed data at 3 different wind farms. Adjustments to biases in the results are also explained. Section 2.4 outlines the equations utilised to calculate the net load, spilled energy, wind energy penetration and capacity factor. Finally, section 2.5 defines 2 optimisation scenarios and their constraints.

2.1. WRF model and setting

The Weather Research and Forecasting (WRF) Model, developed by the US National Centre for Atmospheric Research (NCAR), is a mesoscale numerical weather prediction tool used for atmospheric research and operational forecasting. WRF can generate atmospheric simulations, including wind speeds, using real data observations and analyses or idealized conditions [42]. The model in this study used the ARW (Advanced Research WRF) core and was run on the Australian National Computational Infrastructure at the Australian National University. The WRF model was forced (or nudged) at the boundaries by 2014 NCEP (National Centres for Environmental Prediction) re-analysis data.[13] The NCEP global model assimilates weather observations and historical data. Figure 2 shows the setup of the WRF boundary conditions, which were defined using 2 domains: The 1st domain had a horizontal resolution of 30km and was 130 x 130 grid cells x 30 vertical levels. The 2nd nested domain, encompassing the NE region of Brazil, had a horizontal resolution of 10km and was 166 x 181 grid cells x 30 vertical levels. Hourly wind speed data at specific locations and hub heights above ground level were extracted from the WRF netCDF output files using scripts written in the NCAR Command Language (NCL).

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[13] The NCEP re-analysis data used in the WRF model had a 6 hourly temporal resolution.

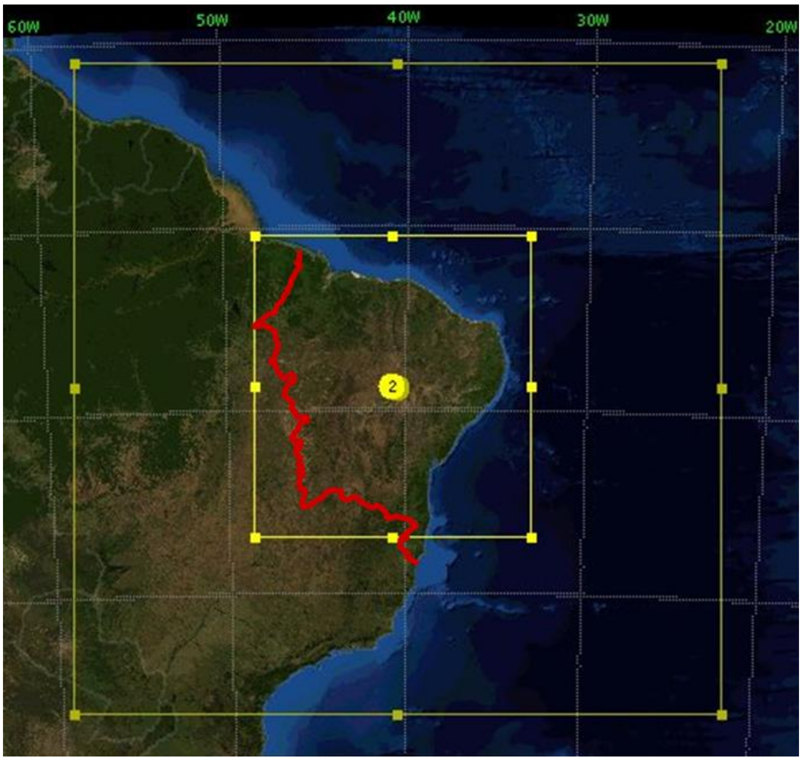

Figure 2: NE region of Brazil and WRF model domains.

The model is first validated by comparing observed wind speed data with the WRF simulation of winds speeds at a few locations where anemometers exist and record average hourly wind speed measurements. Figure 3 shows the Average diurnal wind speeds, at a height of 10m, in Fortaleza, located in the Brazilian NE state of Ceará during October 2014. The observed wind speed data measurements were provided by the University of Wyoming [43]. The hourly WRF wind speed and measured wind speed data have a correlation of 0.62, while the average diurnal correlation between the WRF data and measured data was 0.92.

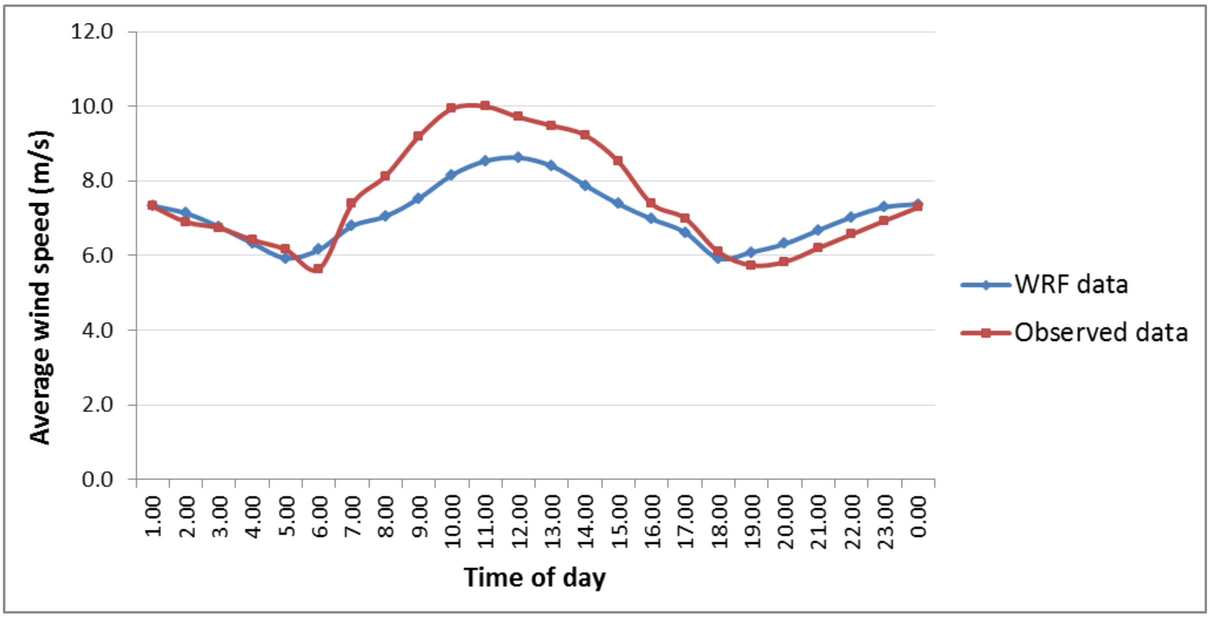

Figure 3: Average diurnal wind speeds during October 2014 derived from the WRF model and measured at Fortaleza airport.

2.2. Wind farm locations and cluster locations analysed using the WRF model

The nominal capacity and location of all wind farms already built, under construction and planned for construction in the NE of Brazil were taken from ANEEL [4]. As there will be approximately 610 wind farms installed across more than 80 municipalities by 2020, in order to simplify the analysis, wind farms were grouped into 30 clusters each consisting of neighbouring municipalities. The large majority of clusters had a radius of less than 30km. Figure 4 and table 1 show the locations of the wind farm clusters. While the majority of wind farms are located in the states of Bahia, Rio Grande do Norte and Ceará, there are also several wind farms located in Piauí and Pernambuco. The nominal capacity in each cluster varies greatly as can be observed in table 1. For example the Caetité cluster in Bahia and the Parazinho cluster in Rio Grande do Norte will have 1635MW and 1876MW of installed wind power, while the Gravatá cluster in Pernambuco will only have 15MW of installed wind power by 2020. Table 1 also shows the approximate elevation of each cluster and if the cluster is located inland or on the coast.

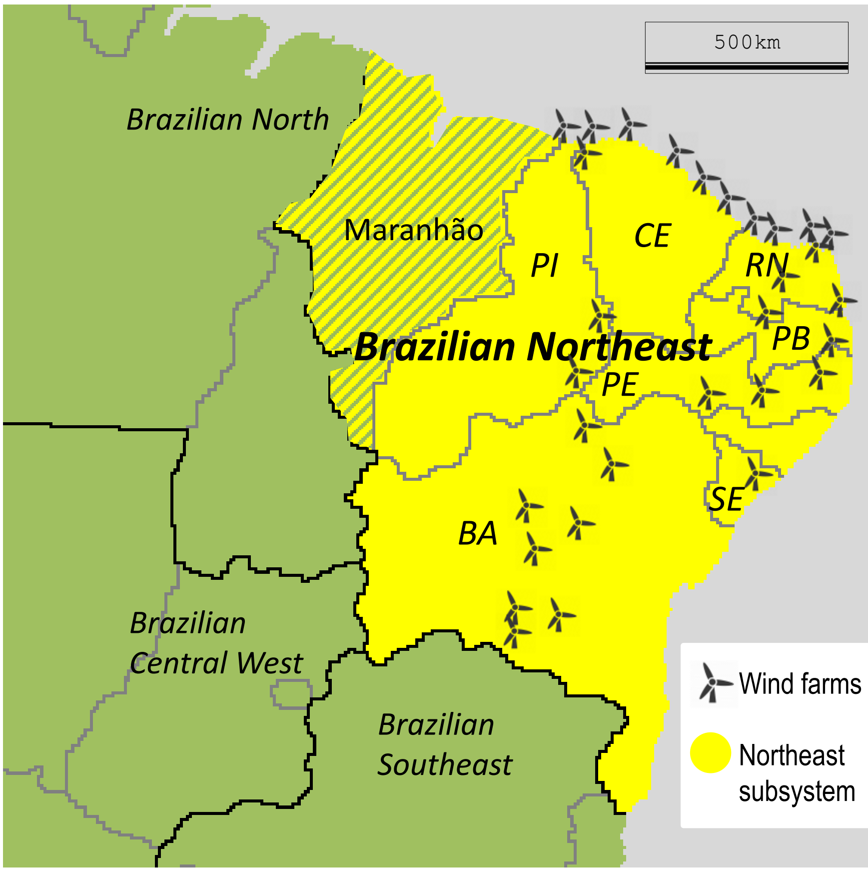

Figure 4: Location of the wind farm clusters in the Northeast subsystem of Brazil. Key: BA – Bahia; CE – Ceará; PB – Paraíba; PE – Pernambuco; PI – Piauí; RN – Rio Grande do Norte; SE – Sergipe. (Note: The state of Maranhão is not included in the Brazilian Northeast subsystem.)

If the majority of turbines in a particular wind farm complex (in the same municipality) were installed before July 2014, it was assumed that the hub height for those wind farms was 50m, unless the hub height is already known. For wind farms installed after July 2014 or for wind farms under construction, it was assumed that the hub height is 80m. For those wind farms planned for construction, it is assumed that the hub height will be 100m.

Table 1: List of wind farm clusters in the Northeast subsystem of Brazil including their location, installed capacity by 2020 and elevation above mean sea level (AMSL). "Coastal" wind farm clusters are within 10km from the coastline unless otherwise stated. (Note: Wind farms located in Maranhão are not included in the Northeast subsystem balancing area and therefore, are not considered in this study.)

State	Latitude°	Longitude°	Cluster Name	Wind Power capacity (MW)	Elevation AMSL (m)	Inland or Coastal
BA	-12.2809	-42.3553	Brotas de Macaúbas	95	1092	Inland
BA	-13.8780	-41.7681	Brumado	90	1102	Inland
BA	-13.9918	-42.6386	Caetité	1635	1070	Inland
BA	-11.7515	-41.3822	Cafarnaum	863	1080	Inland
BA	-10.5725	-40.6306	Campo Formoso	368	920	Inland
BA	-11.4001	-42.5400	Gentio do Ouro	804	1224	Inland
BA	-14.6613	-42.5234	Pindaí	360	772	Inland
BA	-9.7493	-41.1074	Sento Sé	1150	450	Inland
CE	-3.0236	-39.6329	Acaraú	856	10	Coastal
CE	-4.5039	-37.7694	Aracati	415	23	Coastal
CE	-3.8769	-38.3843	Beberibe	94	51	Coastal
CE	-2.9047	-41.0396	Camocim	105	10	Coastal
CE	-3.9417	-40.8753	Tianguá	383	895	Inland
CE	-3.4351	-38.9875	Trairi	724	34	Coastal
PB	-6.5759	-34.9748	Mataraca	63	35	Coastal
PB	-6.8892	-36.9323	São José do Sabugi	90	502	Inland
PE	-8.6632	-36.6714	Caetés	612	930	Inland
PE	-8.2592	-35.6188	Gravatá	15	615	Inland
PE	-7.5156	-35.4649	Macaparana	27	607	Inland
PE	-9.0696	-38.1337	Tacaratu	80	770	Inland
PI	-8.5693	-41.4790	Lagoa do Barro do Piauí	195	600	Inland
PI	-7.3239	-40.6375	Marcolândia	1639	762	Inland
PI	-2.8314	-41.7336	Parnaíba	170	5	Coastal
RN	-4.9468	-36.9714	Areia Branca	535	52	Coastal
RN	-6.0835	-36.5699	Bodó	522	670	Inland
RN	-5.1522	-36.4042	Guamaré	473	30	Coastal
RN	-5.5081	-35.7156	João Câmara	935	125	Coast < 45km
RN	-5.2448	-35.8887	Parazinho	1876	110	Coast < 20km
RN	-5.3238	-35.3871	Rio do Fogo	538	30	Coastal
SE	-10.8113	-36.9302	Barra dos Coqueiros	35	10	Coastal
			Total	**15746**		

The WRF Model is used to simulate hourly wind speeds (for all of 2014) at each of the 30 wind farm cluster locations where wind farms are or will be built in the NE region by 2020. Furthermore, at each cluster location hourly wind speeds were simulated at heights of 50m, 80m and 100m. Then the corresponding hourly wind power is calculated using a standard normalised power curve for typical wind turbines used in the region (see figure 5). The power curve in figure 5 is based on Alstom Eco turbines with rotor diameters of 74-86m and rated power outputs of 1.67-2.0MW. Typically, these turbines have cut-in, rated and cut-out wind speeds of 3m/s, 12-13m/s and 25m/s, respectively [44, 45].

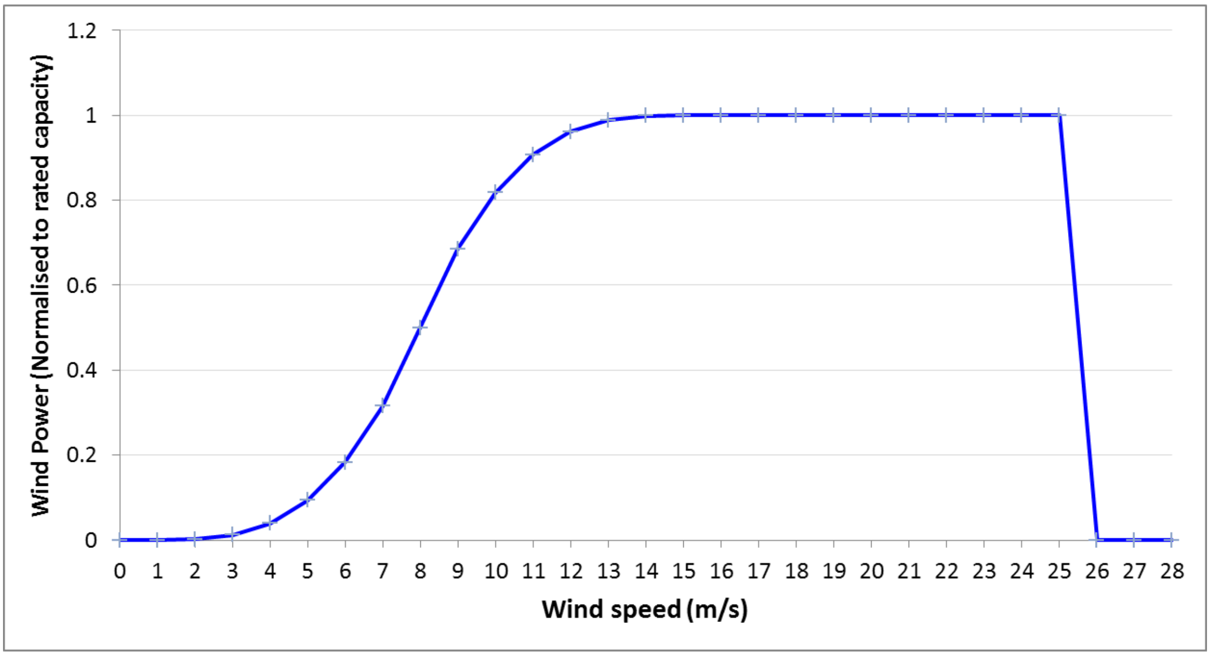

Figure 5: Power curve for a typical wind turbine in the NE.

The normalized hourly wind power data for each cluster location (at hub heights of 50m, 80m and 100m) is then multiplied by the respective installed capacity of wind power in each cluster with the corresponding hub heights. Finally, by summing the results from each cluster for each hour of the year, the aggregate hourly wind power in the NE subsystem is estimated based on the planned wind farm deployment by 2020.

2.3. Model validation

In this section the simulated wind power data is compared to observed data at wind farms located in 3 different states in the Brazilian NE. In section 1.3 it was established that the wind power potential in Bahia is higher at night-time. The prevalence of more wind power at night generated from wind farms in the interior of Bahia was confirmed by the results of the WRF simulation and the observed data for that region (see figure 6). If large scale solar photovoltaic (PV) were installed in Bahia, it would partially complement the diurnal drop in wind generation that typically occurs between 11:00h and 17:00h.

Furthermore, it was found that the observed data and WRF model data for the average hourly (diurnal) capacity factors for a wind farm in Bahia and also for a wind farm in Rio Grande do

Norte had correlations of 0.98 and 0.97, respectively, during the months of August to October (see figures 6 and 7).[14] The correlation between the WRF model data and observed data for the average monthly capacity factors for all of 2014 was 0.93 and 0.90 for these wind farms in the states of Bahia and Rio Grande do Norte, respectively. These high correlations for both the diurnal cycles and season variations of wind power demonstrate that the WRF data is a reliable tool for simulating wind power in both these states. WRF and observed data for other wind farms in the interior of Bahia had similarly high correlations, however for other coastal wind farms in Rio Grande do Norte and Ceará the correlations between observed and simulated data were slightly lower. These results are consistent with the findings of Ramos et al [30] and Pinto et al [31] as both those studies also showed that numerical weather prediction tools were more reliable in the interior than along the coast.

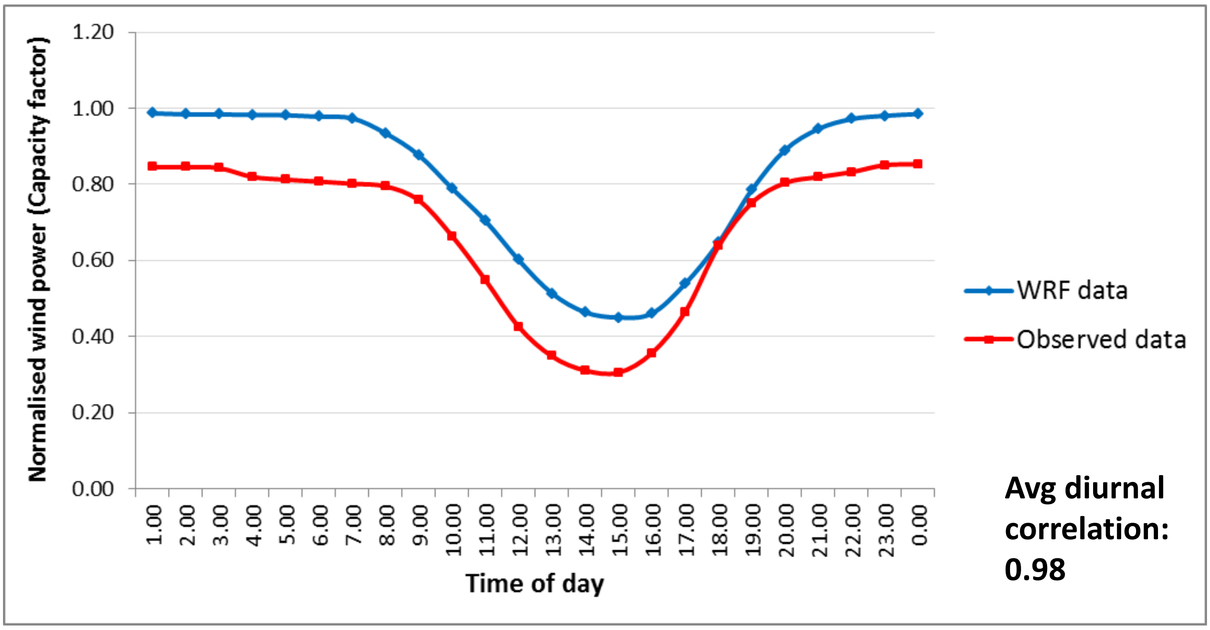

Figure 6: Average diurnal capacity factor for the Novo Horizonte wind farm in Bahia with hub heights of 80m (Aug-Oct 2014).

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[14] Note, while the simulated and observed *average* hourly (diurnal) capacity factors had excellent correlations, the simulated and observed data of the *actual* hourly capacity factors only had correlations of 0.76 and 0.53, respectively, for the Novo Horizonte wind farm in Bahia and the Alegria II wind farm in Rio Grande do Norte.

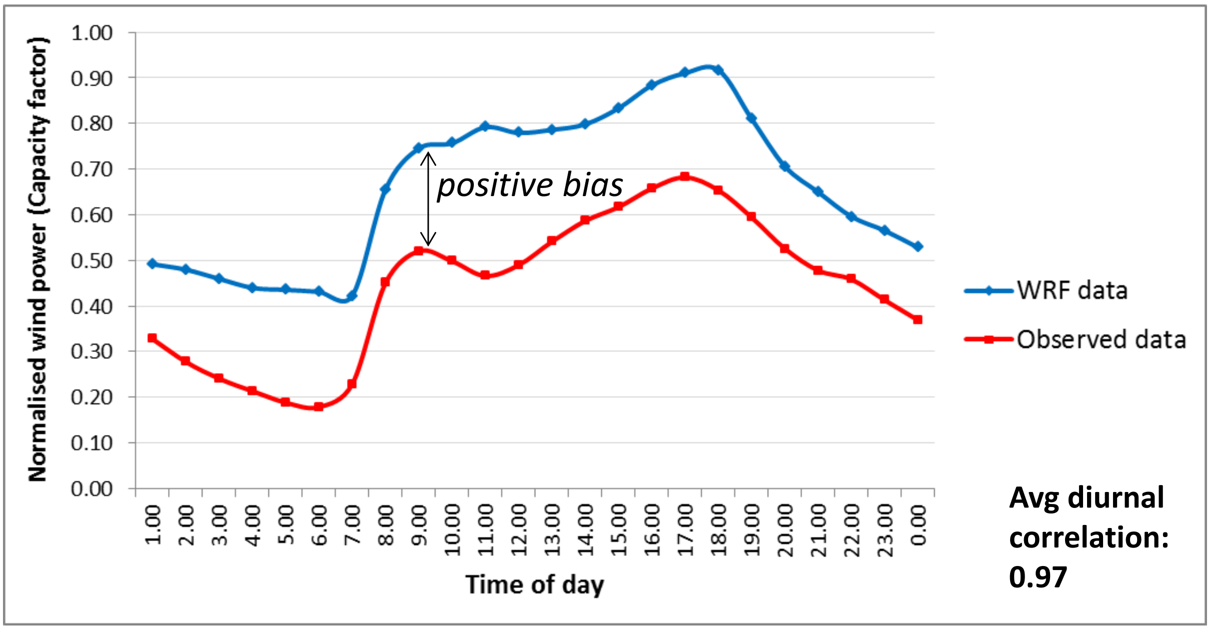

Figure 7: Average diurnal capacity factor for the Alegria II wind farm in Rio Grande do Norte with hub heights of 50m (Aug-Oct 2014).

The average hourly (diurnal) correlation between the WRF model and observed data for the Formosa wind farm in the state of Ceará was slightly less at 0.86 (see figure 8). The correlation between the WRF model data and observed data for the average monthly capacity factors for all of 2014 was 0.86. While the correlations for the Formosa wind farm in Ceará are not as good as for the two wind farms analysed in the states of Bahia and Rio Grande do Norte, they are satisfactory for the purpose of this study.

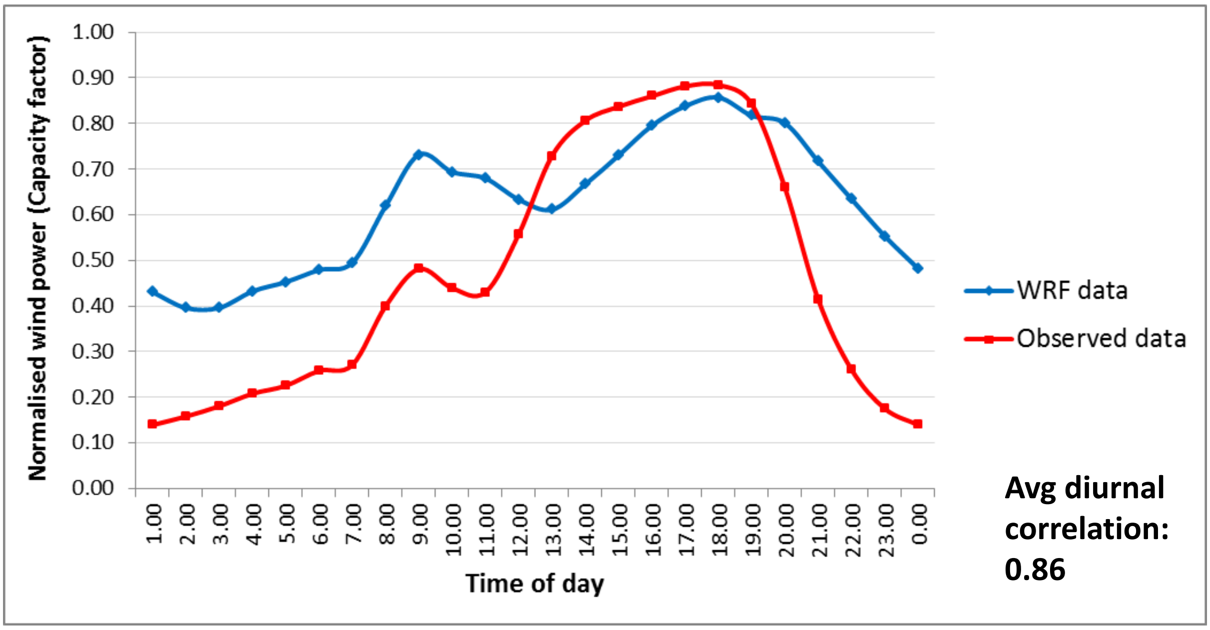

Figure 8: Average diurnal capacity factor for the Formosa wind farm in Ceará with hub heights of 50m (Aug-Oct 2014).

Furthermore, it was found that the wind power results derived from the WRF data were typically higher than the observed measurements (see figures 6 and 7). This positive bias is consistent with the findings of Carvalho et al [28] and Oliveira [32], and occurs because the WRF model does not resolve for turbulence and small scale topography. On the other hand, WRF simulations for wind power in Ceará were marginally lower than observed measurements considering all of 2014. It should be noted that the majority of existing wind farms in Ceará were built on sand dunes. Sand dunes typically have a very low roughness and this may explain the slightly negative bias of WRF results in Ceará compared to the positive bias in other states.

Therefore, in all simulations, the wind power results derived from the WRF data were adjusted to match measured data. Specifically the hourly WRF capacity factor data was multiplied by a constant derating factor, which was calculated by comparing WRF derived and observed average aggregate wind power capacity factors for different states during all of 2014. Overall observed capacity factor data for installed wind farms in the states Bahia, Ceará and Rio Grande do Norte for all of 2014 was taken from the Operador Nacional do Sistema Elétrico / Brazilian National Electricity System Operator [46] while WRF derived capacity factor data was calculated based on WRF data for the same installed wind farm locations. The derating factors used in the simulation for Bahia, Ceará and Rio Grande do Norte were 0.823, 1.07 and 0.67, respectively. The average of these three derating factors (0.857) was used for the other states as observed data was not available.

2.4. Net load, spilled energy, wind penetration and capacity factor calculations

Using the aggregate hourly wind power data, the hourly net load and spilled energy are estimated in the Brazilian NE subsystem based on the planned wind farm deployment and expected load by 2020. The NE subsystem hourly electricity load data was estimated from the ONS [47] in the same manner as per the initial study by de Jong et al [9]. That is, electricity demand from the NE subsystem in 2020 was estimated by extrapolating the annual growth in demand from 2005 to 2014 which was 4.1% [48, 14].

The operational flexibility of a power system was defined by Ulbig & Andersson [49] as its ability to quickly modulate electricity generation to effectively balance supply with net demand. Introducing more variable power generation, such as wind power, increases the need for flexibility in a power system particularly on the supply side, but demand side management can also play a role [6, 8, 50, 51]. Coal and especially nuclear base-load generation have stringent minimum run levels and operational ramp rate constraints [6, 8, 50]. However, the NE subsystem has no nuclear plants and coal plants only make up less than 4% of the total installed generation capacity.[15] Hydroelectric and open cycle gas turbines can quickly ramp supply up (or down) to balance demand and are typically used as flexible load-following plants [6]. Therefore, initially it was assumed that existing hydroelectric and gas generators, which predominate in the NE subsystem, have 100% scheduling flexibility to effectively supply the net load.

While the flexibility of hydroelectric plants is ideal for the integration of variable wind energy generation, it can be constrained by environmental regulations governing the preservation of aquatic ecosystems [52, 53]. Though, it should be noted that ecological constraints on hydropower generally occur on longer time scales [53] than hourly intervals important for wind integration.[16] Nevertheless, for all proceeding scenarios, an 80% scheduling flexibility is used based on the hydroelectric minimum flow requirements of 800-1100m^3/s along the São Francisco River [54, 55] which equates to a minimum generation level of approximately 2500MW [14, 34].

Constraining the minimum run of hydroelectric plants to 20% of the average load in the simulations also ensures that 20% synchronous generation is always operating in the power system. According to AEMO [56] at least 15% of synchronous generation is required in a power system because the mechanical inertia of synchronous generators inherently provide some natural damping of frequency deviations. Electromagnetic and kinetic inertia are important indicators to quantify the reliability of a power system to sudden power imbalances [57], however, analysis of transient disturbances is beyond the scope of the net load approach used in this study.

As per Nikolakakis and Fthenakis [7], energy was defined as spilled or surplus if the hourly net load was less than the NE's minimum generation level (*min*Generation). Thus, the total

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[15] Additionally, the NE subsystem has a small percentage of combined cycle gas turbines. Combined cycle gas turbines are not as flexible as hydroelectric and open cycle gas turbines, nevertheless they only require 5 minutes to start up (from cold) and can ramp up to full power within 1-2 hours [6].

[16] For example, during the early hours of the morning on days when peak wind generation occurs, hydroelectric output could be reduced to below its minimum generation level in order to minimise wind energy curtailment, provided that the overall average hydroelectric minimum generation is maintained on a daily basis.

spilled energy is the sum of the net load minus the *min*Generation level, for each hour where the net load was less than the *min*Generation level. Furthermore, it is assumed that the average annual useful generation and average annual load in the NE subsystem are approximately equal and hence the average spilled energy as a percentage of the average (Avg) load can be calculated as follows:

$$\%\ \mathit{Spilled\ Energy} = -\{\Sigma_{hour}\ (\mathit{Net\ load}_{hour} - \mathit{minGeneration}),\ \mathit{if\ Net\ load}_{hour} < \mathit{minGeneration}\ \} \times 100 / (\mathit{no.\ of\ hours} \times \mathit{Avg\ load}) \tag{1}$$

The gross and net wind power penetration in the NE subsystem were defined as follows:

$$\%\ \mathit{Gross\ penetration} = \mathit{Avg\ annual\ wind\ power} \times 100 / \mathit{Avg\ annual\ electricity\ load} \tag{2}$$

$$\%\ \mathit{Net\ penetration} = \%\ \mathit{Gross\ penetration} - \%\ \mathit{Spilled\ Energy} \tag{3}$$

Similar to [7] and [8], surplus wind energy for the NE subsystem is plotted against increasing amounts of wind power penetration. The average wind power capacity factor for the NE subsystem was calculated as follows:

$$\mathit{Avg\ Capacity\ Factor} = \mathit{Avg\ annual\ wind\ power} / \mathit{Nominal\ installed\ wind\ power\ capacity} \tag{4}$$

As explained by [34] and [37] transmission congestion can be a cause of additional curtailment. However, transmission constraints have been omitted from the analysis in this study, because transmission systems can be expanded and fortified to largely prevent curtailment caused by congestion at a relatively small cost considering total power system costs [37, 58]. Furthermore, transmission congestion and the cost of new transmission infrastructure are not specifically problems caused by variable renewable energy sources, but rather, apply to all generation technologies. In fact, in Brazil the costs of new lengthy transmission lines for new large scale hydroelectric plants, typically located very far from load centres, significantly outweigh the costs of new transmission for wind and solar power plants [10]. Additionally, transmitting large amounts of electricity long distances across the country also incurs significant energy losses.

2.5. Optimisation scenarios

In the baseline scenario, the aggregate hourly wind power and net load for the NE subsystem are calculated based on planned wind farm deployment until 2020. This baseline scenario is extended beyond 2020 to estimate higher penetrations of wind power in the NE region. The percentage of spilled or surplus energy is calculated for gross wind energy penetrations up to

120%. It is assumed that the proportions of installed wind power in each cluster will not change significantly with future growth in wind power penetration beyond 2020.

In the second and third scenarios it is assumed that the installed wind power capacities are entirely flexible up to a maximum of 3000MW per cluster. That is, in these scenarios the amount of wind power already installed or planned for installation in each cluster is not taken into consideration. A maximum of 3000MW of installed wind power per cluster was chosen because there are physical limits to the number of wind turbines that can be installed in a finite area, as well as transmission constraints in the grid. This cap is approximately a 50% increase in the installed capacity of the largest clusters in the baseline scenario. While cluster areas are almost 3000km^2 each and theoretically, substantially more wind power capacity could be installed in each cluster, in practice there are always constraints due to the type of terrain, accessibility and transmission limits. Furthermore, in practice cluster sizes are likely to vary from one another, however, this level of detail is beyond the scope of this study.

A spreadsheet optimisation tool is used to find the optimal installation capacities in each cluster according to the specific objectives in each scenario. The tool's "Generalized Reduced Gradient Nonlinear" engine typically uses 40 or more iterative trails to converge and find an optimal solution that satisfies all constraints. In the second scenario the locations of wind farms are optimised in order to achieve maximum annual wind energy penetration while limiting the amount of surplus or spilled energy to 1% and 5%, respectively.

In the third scenario the locations of wind farms are optimised in order to maximise the overall wind power capacity factor and then maximum annual wind energy penetration while limiting the amount of surplus or spilled energy to 1%, 5% and 10%, respectively. The levelised cost of electricity (LCOE) of wind energy in the NE region has been calculated in [10] and is inversely proportional to the amount generated electricity. Given that the generated electricity is proportional to the average capacity factor, it is assumed that the LCOE of wind farm clusters in the NE is inversely proportional to the capacity factor of each cluster. Furthermore, it is assumed that other variables that influence the LCOE such as installation and maintenance cost do not vary significantly in the NE region. Therefore, it is assumed that those wind farm clusters with the highest annual capacity factors have the lowest LCOE. Hence, in this scenario the location of wind farms is optimised in order to achieve least cost.

The gross (and net) penetration and the overall wind power capacity factors are calculated for each scenario. Furthermore, the locations of the wind farm clusters required to achieve both maximum wind energy penetration (scenario 2) and maximum wind power capacity factor (scenario 3) are shown on separate maps of the NE region.

3. RESULTS AND DISCUSSION

Installed wind power in the NE subsystem of Brazil will grow to almost 16000MW by 2020 [2, 11]. Considering all the wind farms in the NE subsystem already installed and those contracted for operation, it is estimated that wind power will generate approximately 57% of the NE's annual electricity demand by 2020. In spite of this high penetration, only 0.2% of the NE's total generation would need to be curtailed or *exported* to other Brazilian regions, assuming that the NE's existing hydroelectric generators have a minimum generation level of zero and 100% scheduling flexibility to effectively balance the net load. Assuming that new wind farms to be installed after 2020 will be installed in the same clusters and that the *proportions* of installed wind power capacity in each cluster remain approximately the same as in table 1, the baseline scenario is extended to estimate higher penetrations of wind power in the NE subsystem. It was found that the maximum wind power penetration in the NE region could reach 63% while only 1% of electricity generation would need to be curtailed, stored or *exported* to other regions annually.

However, in all the following analyses it is assumed that the São Francisco River's hydroelectric generators have minimum flow rates due to ecological reasons (such as to avoid salination in the lower São Francisco), which equate to a minimum generation level of 2500MW and therefore, the flexibility of the dispatchable hydroelectric and open cycle gas generators would be constrained to approximately 80%. That is, considering this minimum generation level, hydroelectric plants would be required to generate at least 20% of the NE's average electricity demand at all times or alternatively spill water. Under these constraints and considering that wind energy will generate 57% of the NE's electricity demand, approximately 3.1% of the NE's total generation would need to be curtailed or *exported* to other Brazilian regions by 2020. In fact, under these constraints, once wind energy penetration in the NE reaches approximately 50%, at least 1% of the NE's total generation would need to be curtailed or *exported* to other regions.

3.1. Wind power capacity factor variations

According to the WRF simulation of wind power by 2020, the annual capacity factors for the states of Bahia, Ceará, Rio Grande do Norte, Piauí and Pernambuco are predicted to be 50.2%, 45.4%, 37.6%, 43.0% and 40.3%, respectively. The entire NE subsystem's average annual capacity factor for all wind farms planned for operation by 2020 is estimated to be 44%. However, the NE's monthly wind power capacity factors vary significantly, dropping below 30% in the autumn months (March, April and May) and reaching above 50% from August to October (see figure 9). In comparison, the NE subsystem average monthly load varies less 10% during a typical 12 month period (see figure 9). Nevertheless, it can also be observed in figure 9 that the monthly wind power capacity factors have a complementarity with the amount of stored hydroelectric energy in the NE subsystem. This is consistent with findings from the initial study by de Jong et al [9] and Schmidt et al [25]. Therefore, wind power production in the NE region will improve energy security and save water in the São Francisco basin, particularly toward the end of the dry season when NE reservoir volumes drop to their lowest levels. Moreover, as average rainfall levels are predicted to decline in the long term due to climate change, wind energy (which will generate the majority of the NE's electricity by 2020) could replace lost hydroelectric annual availability.

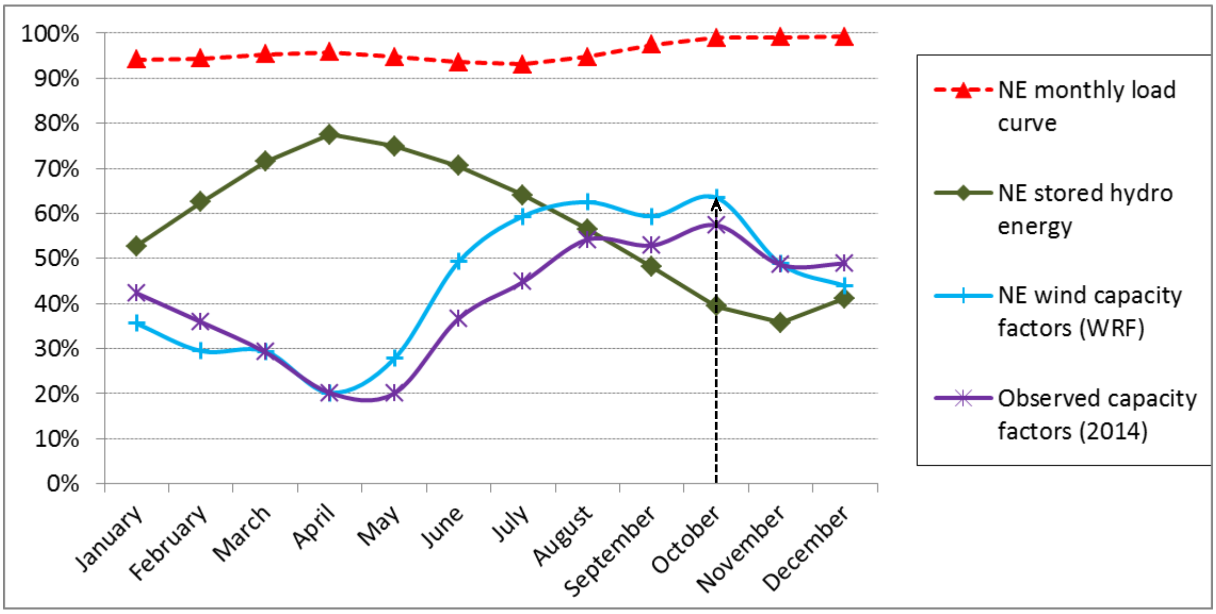

Figure 9: NE long-term average stored hydro energy compared with wind power monthly capacity factors and NE subsystem load.

Additionally, figure 9 shows that the observed monthly wind power capacity factors differ slightly from the WRF simulation. However, this is to be expected because the observed aggregate monthly capacity factor data only considers wind farms that were already installed in 2014, while the WRF simulation considers all wind farms expected to be operational by 2020 (which includes several with hub heights of 100m). Nevertheless, it can be observed that the maximum wind power production occurs in the months of August to October for both measured data and the WRF simulation. Observed wind power data for 2013 and WRF simulations for the second semester of 2013 also indicated that maximum production occurred between August and October. This study assumes that diurnal and seasonal wind patterns will not change significantly from year to year. Nevertheless, it should be noted that 1 to 2 years of wind data is not very representative in terms of climatology. Furthermore, by the second half of the 21st century, wind power is likely to increase substantially in the NE region due to the effects of climate change [18, 59], and the impacts of global and regional warming could also alter the diurnal and seasonal wind patterns in the long term.

Figure 10 shows the NE wind power "duration curve" based on the aggregate installed wind power capacity for 2020. It was calculated from the WRF simulation, that the aggregate hourly capacity factor of all the NE wind farms only drops below 5% for approximately 2% of the time annually (considering all 8760 hours in the year) and drops below 10% for less than 6% of the time (see figure 10). It is anticipated that during these hours of low wind power, the resulting high net load can be balanced by the large amount of hydroelectric capacity (approximately 11,000MW) already operating in the NE region [4], as well as from biogas/biomass generation and imported hydroelectricity. Furthermore, according to the WRF simulation of 2014 wind speeds, the aggregate hourly capacity factor of all the NE wind farms never exceeds 80%.

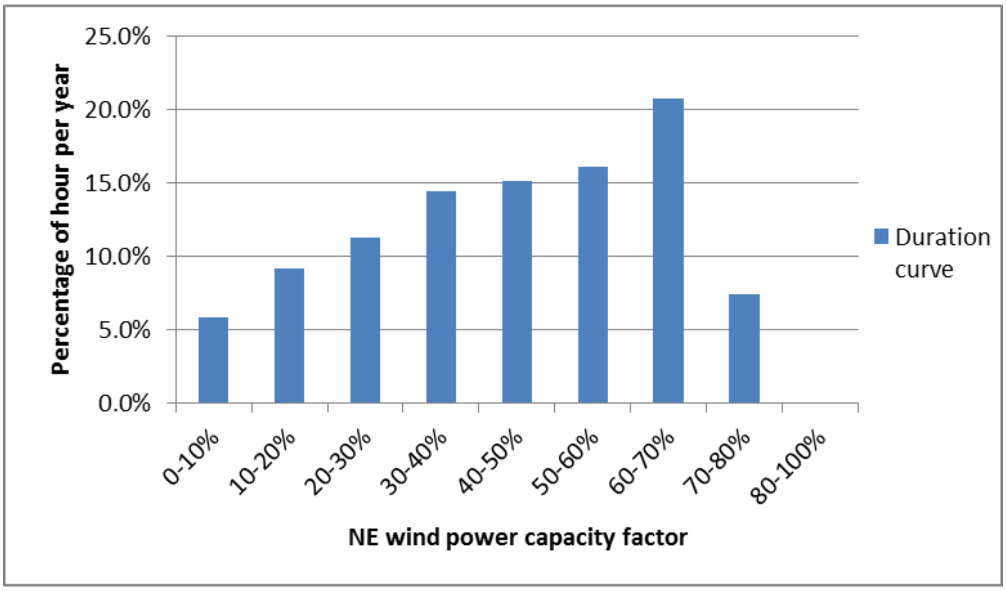

Figure 10: Histogram of aggregate NE wind power capacity factors based on installed capacities for 2020.

3.2. Hourly variations in wind power production

As stated early, wind energy penetration in the NE subsystem is projected to reach 57%, based on the total amount of wind power capacity contracted for deployment by 2020. The aggregate hourly wind power and net load for the NE subsystem is calculated for this baseline scenario and the results for a typical day in the month of October are shown in figure 11. The month of October was chosen because in 2014 the maximum average wind power production occurred in the month of October. Note that in this baseline scenario wind farms are installed and located according to table 1 and figure 4. In figure 11 it can be observed that the net load curve drops below the NE's hydro minimum generation level between the hours of midnight and 08:00h which is an indication of surplus generation that would need to be curtailed or *exported*. While it was calculated there would be approximately 3.1% of surplus wind energy annually, the large majority (approximately 2.8%) of surplus wind energy would occur during the months of June to November, especially between midnight and 08:00h. Therefore, demand side management could play a role in reducing surplus energy in the NE region. For example, consumers could be offered a discount tariff during these periods of surplus generation.[17] Similarly, farmers could be encouraged to use this excess generation to operate irrigation pumps after midnight. The best time to irrigate crops is after midnight, as this reduces evaporation losses [60] and the dry season in the NE's semi-arid areas occurs between May and November.

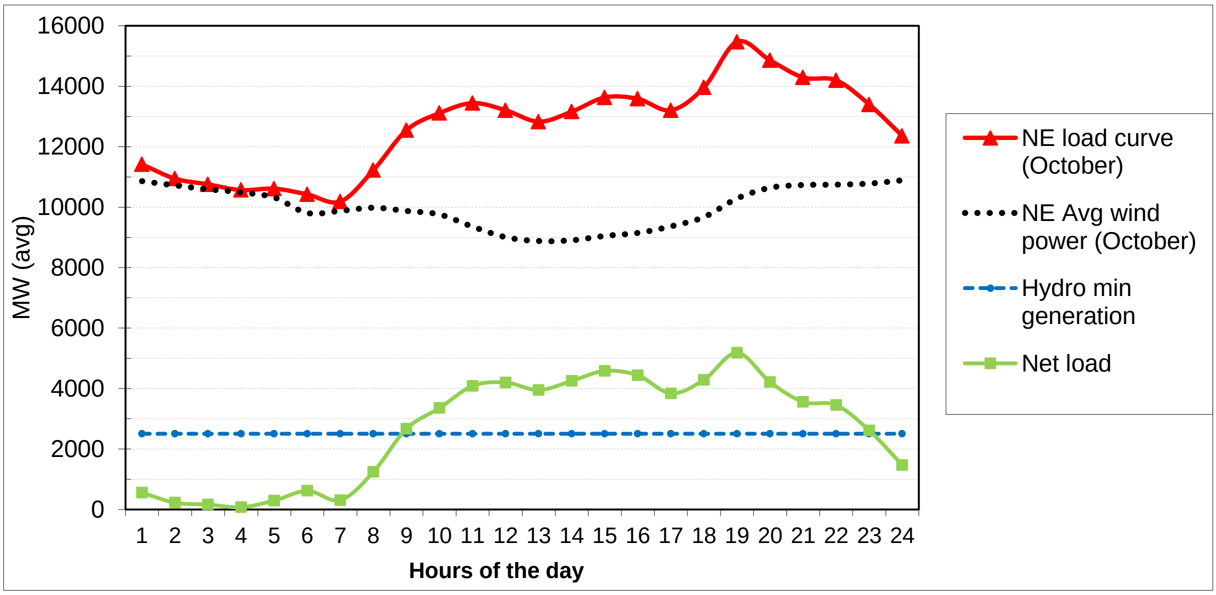

Figure 11: Average hourly load curve, aggregate diurnal wind power output, hydro minimum generation and net load curve in the NE during October based on installed capacities predicted for 2020.

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[17] Actually, from 2018, consumers in Brazil will be able to opt for a time of day based tariff called the *"tarifa branca / white tariff"* which is designed to encourage consumers to reduce electricity consumption during peak demand periods (between 18:00h and 22:00h).

3.3. Adding solar generation to the baseline scenario

Given that the NE's net load is still 2700-4500MW between the hours of 09:00h and 16:00h (even in the month of October when wind energy generation is at its highest), a small amount of solar PV could be installed in the region without significantly increasing the amount of curtailment. A total of 1850MW of grid connected PV has been planned for installation in the NE by 2020 [4]. Therefore, it is estimated that PV will generate approximately 4% of the NE's 2020 electricity demand.[18] However, the amount of surplus generation that would need to be curtailed or *exported* annually would increase from 3.1% (in the baseline case with 57% wind penetration) to 3.9% considering the case with 57% wind penetration and 4% solar penetration. Together wind and solar energy will have a gross penetration of 61%, while hydroelectricity (and where necessary biogas/biomass turbines) could make up the remaining generation to balance the NE's load. In the month of October wind, solar and hydro power would generate 79%, 4% and 17% of the NE's electricity load while approximately 9% (shown as surplus hydro generation) would need to be *exported* (see figure 12). Therefore, the addition of solar power to existing hydroelectric plants and planned wind farms should complement and further diversify the NE's generation matrix, which by 2020, could become a net exporter of electricity. These results also confirm that virtually all fossil fuel generation in the NE subsystem could be substituted with mostly wind energy, even considering reduced hydroelectric production caused by moderate drought conditions [9] or due to climate change.

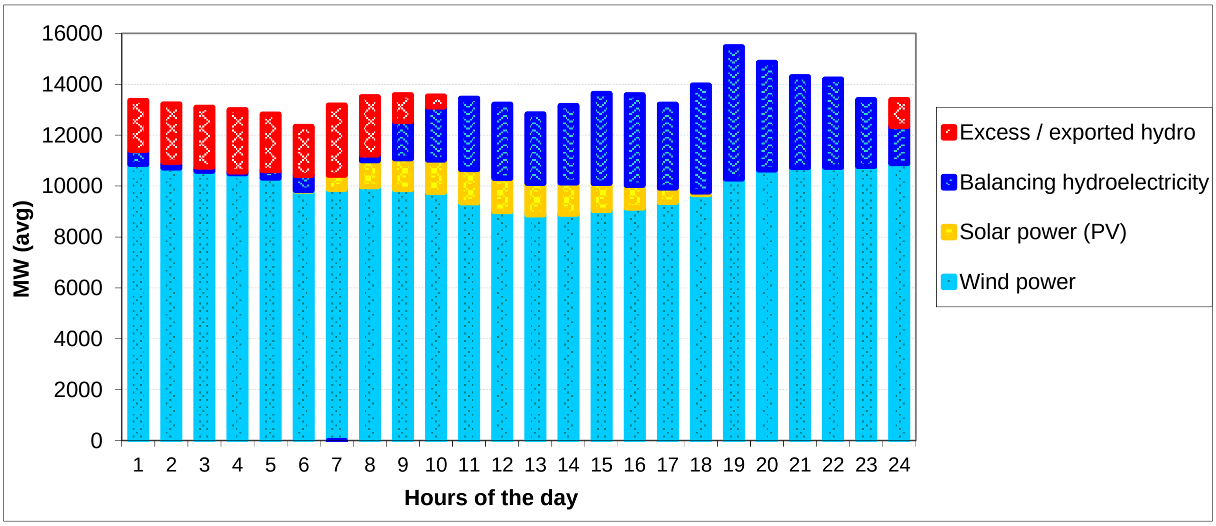

Figure 12: Aggregate diurnal wind power, average hourly solar power and balancing hydroelectricity supplying the NE's electricity load during October. Excess power is shown in red as *exported* hydro in order to maintain the minimum generation of hydroelectric plants. Note, that in reality the *exported* electricity is likely to be a combination of wind, hydro and solar power depending on the location of generators and transmission links.

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[18] Note, hourly solar PV generation for the NE was estimated using "NREL's PVWatts Calculator: Hourly PV Performance Data" for Bom Jesus da Lapa, Bahia.

3.4. Adding more wind power to the baseline scenario

In this analysis the baseline scenario is extended with additional wind power capacity to estimate the impact of higher penetrations of wind power in the NE region. Allowing for up to 10% surplus generation in the NE subsystem, the maximum gross and net wind energy penetration in the region were estimated to be 70.5% and 60.5%, respectively, provided sufficient transmission infrastructure is implemented to distribute this amount of wind power. In this scenario, the annual wind power capacity factor was estimated to be 44.6%. The aggregate hourly wind power and net load for the month of October considering this scenario can be observed in figure 13. In October wind power would generate on average 98% of the NE subsystem's average load. Therefore, while 10% surplus generation would need to be spilled or *exported* annually, in the month of October there would be approximately 22% of surplus generation in the NE subsystem that would need to be curtailed or *exported*.

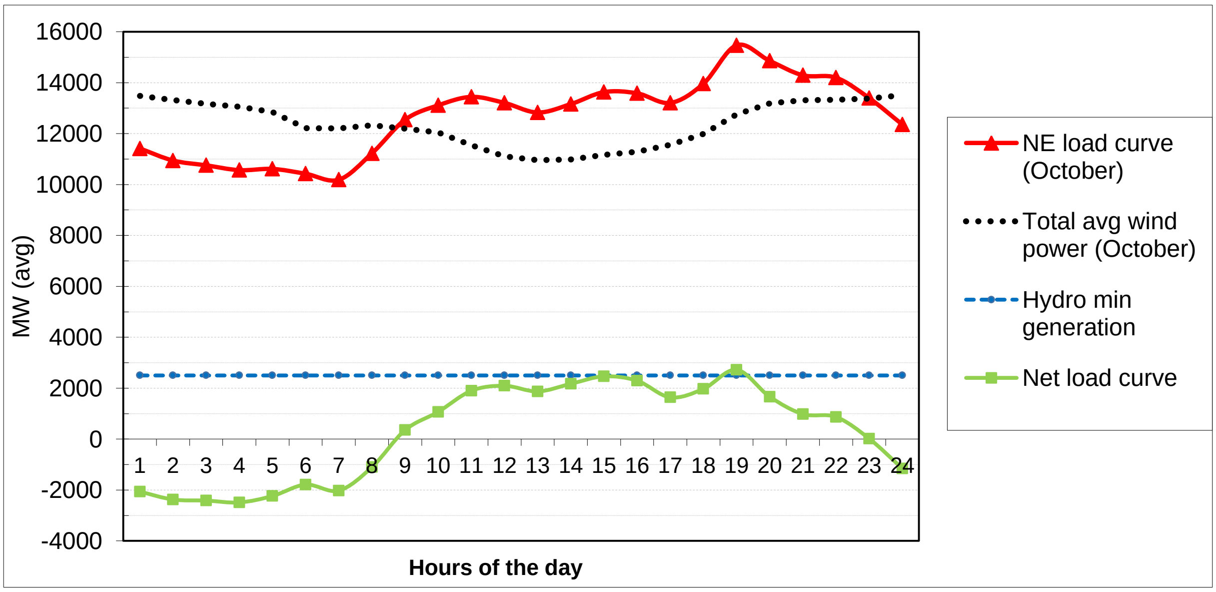

Figure 13: Average hourly load curve, total aggregate diurnal wind power output, hydro minimum generation and net load curve in the NE during October considering 70.5% gross wind power penetration in the NE.

In table 2 and figure 14 the average surplus energy as a percentage of the NE subsystem's average load is shown with increasing amounts of wind energy penetration considering both 80% and 100% grid flexibility. As before, with 80% grid flexibility, the hydroelectric minimum generation level is 2500MW, while with the 100% grid flexibility case, hydroelectric generation can drop to zero. The percentage values for wind power penetration and average surplus generation are based on the NE subsystem's average load estimated to reach 12,250MW$_{avg}$ by 2020. In Figure 14 the baseline scenario with 80% grid flexibility is shown by the solid lines. Note that above a gross wind penetration of approximately 60%, the percentage of surplus generation begins to climb rapidly. The baseline scenario with 100% grid flexibility is shown by the dotted lines and it can be observed that above a gross wind penetration of approximately 75%, the percentage of surplus generation begins to climb rapidly.

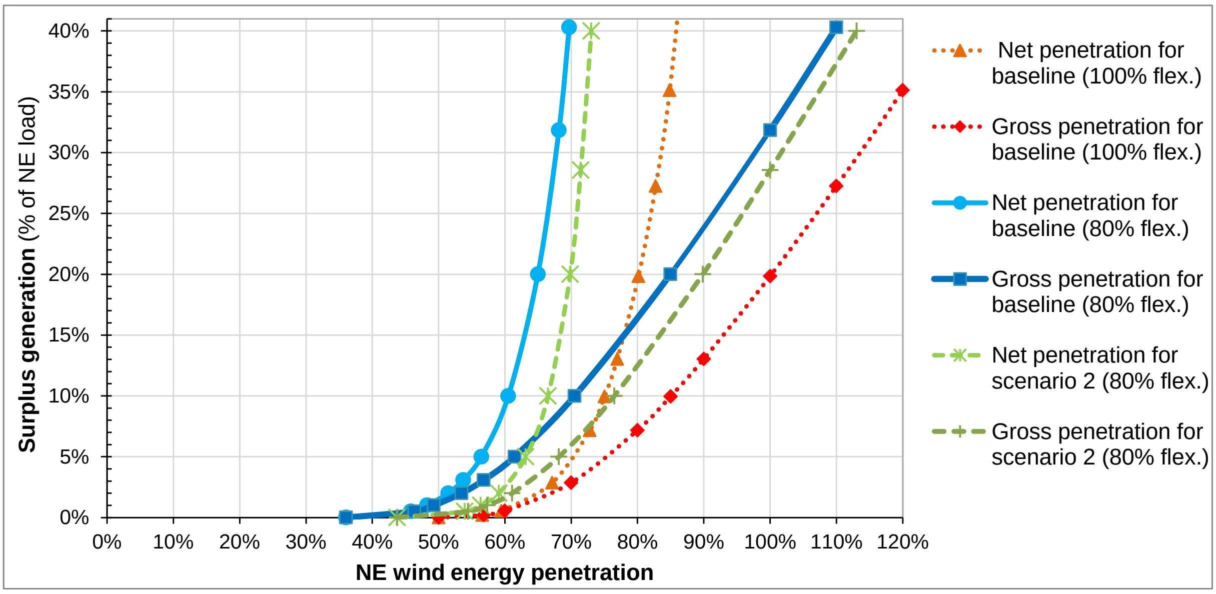

Figure 14: Percentage of surplus generation versus gross and net wind energy penetration in the NE subsystem considering the baseline scenario (with 80% and 100% grid flexibility) and scenario 2 with 80% grid flexibility.

Table 2 shows the average annual surplus generation as well as the maximum instantaneous surplus power in the entire year for different amounts of installed wind power. The values shown in bold reflect the expected situation in the NE region by 2020.

Table 2: Comparison of surplus generation in the NE region for different amounts of installed wind power, considering both 80% and 100% grid flexibility. The absolute installed wind power capacity and the gross wind penetration are shown in columns 1 and 2, respectively. In columns 3-6, both the average annual surplus generation and the annual maximum instantaneous surplus power are shown.

		100% grid flexibility:		**80% grid flexibility:**	
Installed wind power capacity (MW)	**Gross wind penetration** (%)	**Avg surplus generation** (%)	**Max surplus power** (MW)	**Avg surplus generation** (%)	**Max surplus power** (MW)
11304	40%	0.0%	0	0.02%	845
13948	50%	0.001%	319	1.1%	2819
15746	**57%**	**0.2%**	**1662**	**3.1%**	**4162**
16592	60%	0.6%	2294	4.3%	4794
19235	70%	2.9%	4327	9.7%	6827
23201	85%	10.0%	7400	20.0%	9900
27166	100%	19.8%	10472	31.8%	12972

Given the proximity of several wind farms in the south of Bahia to Minas Gerais in the Southeast region and taking into account transmission limits, it is anticipated that large amounts of surplus wind energy will be *exported* to that region. Transmission lines interconnecting the NE subsystem to the Brazilian Southeast and North subsystems currently have capacities to allow up to 4300MW and 4400MW of power to be *exported* to these respective regions [61]. Therefore, considering the maximum surplus power results shown in column 6 of table 2, the following conclusions can be made. While gross wind penetration in the NE remains below 57%, surplus generation could be exported solely to the Southeast region. Above this penetration, some surplus energy would also need to be exported to the North region assuming it can absorb it. Once gross wind penetration reaches 80%, at least some energy would need to be curtailed or spilled (unless the capacity of the NE’s interconnect transmission links are increased).

Energy storage is an alternative to curtailment or *exportation*. Pumped hydro storage is an efficient large scale technology that could be used to store surplus generation from variable renewable sources [38, 62], however, storage would only be worthwhile if it proved more economically viable than curtailment or upgrading interconnect transmission lines for *exports*.

3.5. Hourly variations in wind power production considering optimisation scenario 2

In the baseline scenarios the proportions of installed wind power capacity in each cluster were fixed. In the following optimisation scenarios (scenarios 2 and 3) the installed wind power capacities at all wind farm locations (clusters) are entirely flexible (up to a maximum of 3000MW per cluster). In scenario 2, the installed capacity of wind farms in each cluster is optimised in order to achieve maximum annual wind energy penetration while limiting the amount of spilled energy to 1% and 5%, respectively. This flexibility allows for the simulation to only *install* wind farms in clusters where the seasonal and diurnal wind power output best matches the daily load curve. As a result, in scenario 2 it was calculated that a maximum wind energy penetration of 57% could be attained in the NE region while only 1% surplus generation would need to be curtailed or *exported* to other regions. The aggregate hourly wind power and net load during the month of October for scenario 2 can be observed in figure 15.

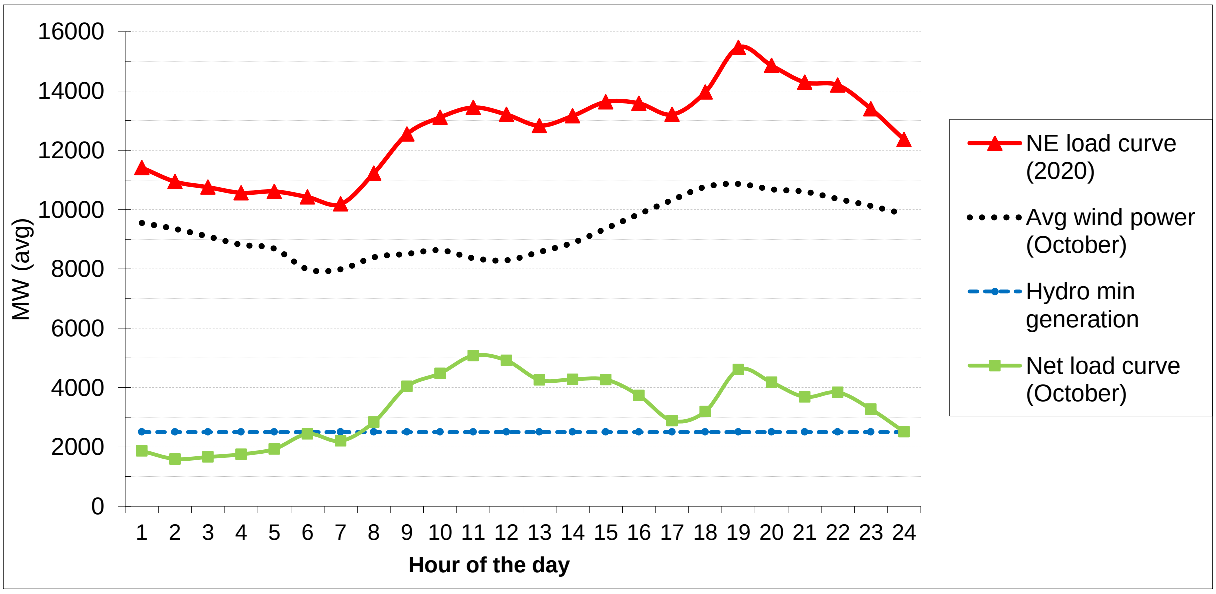

Figure 15: Average hourly load curve, aggregate diurnal wind power output, hydro minimum generation and net load curve in the NE during October for scenario 2.

In this second scenario with 57% wind power penetration it was calculated that the annual wind power capacity factor would be 43.8%. In this scenario wind farms would need to be built across 9 different cluster locations with various installed capacities (see figure 16). (Note that allowing for up to 5% of electricity generation to be spilled or *exported* would enable the maximum gross wind power penetration in the NE region to reach 68%).

Only a small amount of wind power would be required in Paraíba, Pernambuco, Sergipe and Bahia while the majority would need to be installed in Rio Grande do Norte. Moreover, with the exception of the wind farm cluster in the south of Bahia, the majority of the wind farms in scenario 2 are grouped together in the eastern part of the NE region and therefore the spatial distribution of wind farms is significantly smaller than in the baseline scenario.[19]

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[19] It should be noted that diurnal wind power from coastal wind farms in the state of Ceará also correlates well with the daily load curve even though these wind farms did not appear in the results of optimisation scenario 2.

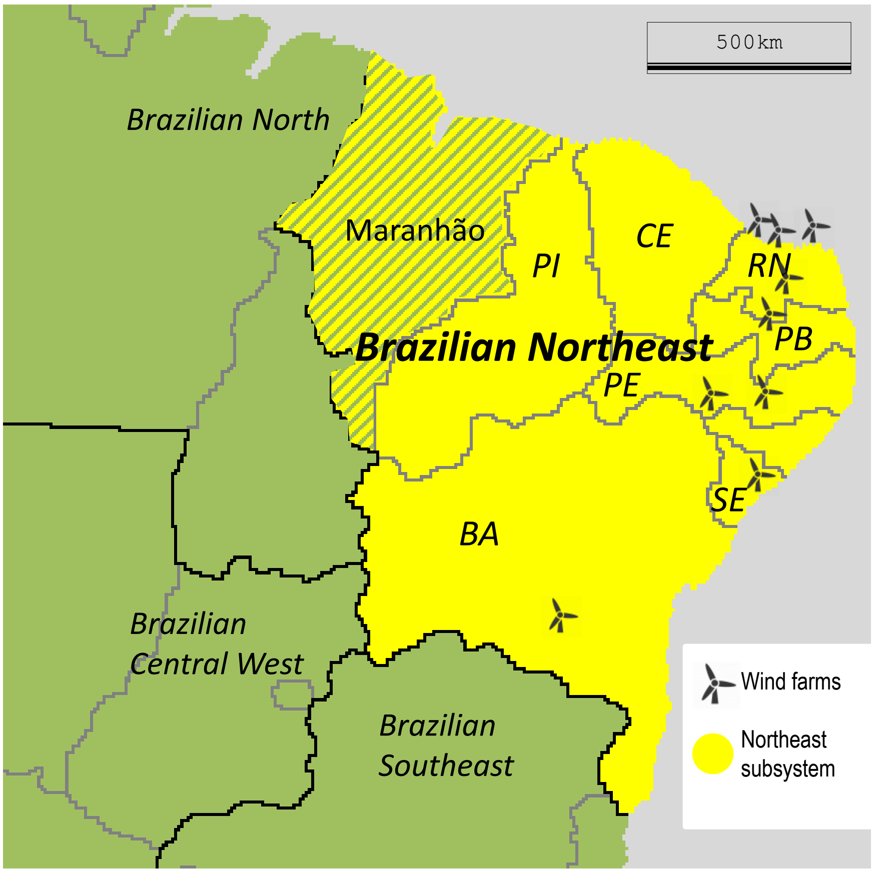

Figure 16: Location of the wind farm clusters in the Northeast region of Brazil for scenario 2. Key: BA – Bahia; CE – Ceará; PB – Paraíba; PE – Pernambuco; PI – Piauí; RN – Rio Grande do Norte; SE – Sergipe.

In figure 14 the average amount of surplus generation as a percentage of the NE subsystem's average load is plotted against increasing percentages of wind energy penetration for the baseline scenario (shown by the solid lines) and for scenario 2 (shown by the dashed lines). While the maximum gross penetration limit is 49.3% with negligible (up to 1%) spilled energy in the baseline scenario, in the second scenario the maximum gross penetration reaches 57% with negligible (up to 1%) spilled energy. Note that in scenario 2 the percentage of surplus generation begins to climb rapidly above a gross penetration of approximately 70%.

It is worth noting that with a gross wind energy penetration of 70.5% in the baseline scenario, there would be 10% surplus generation, whereas in scenario 2, with the same gross wind penetration, there would be only 6.3% of surplus generation. While a gross wind energy penetration approaching 120% is perhaps hypothetical, figure 14 shows that even considering scenario 2, the *net* wind energy penetration is limited to a maximum of approximately 75%.

3.6. Daily variations in wind power production considering optimisation scenario 3

In scenario 3 the installed capacity of wind farms in each cluster are optimised in order to achieve a maximum annual aggregate wind power capacity factor and as a second priority maximum wind energy penetration with negligible spilled energy. This optimisation scenario allows for the simulation to only *install* wind farms in clusters with the highest annual wind power capacity factors and thus minimise wind generation cost. Therefore, in scenario 3 it was found an annual capacity factor of 57.7% could be obtained utilising only these specific wind farm clusters. In this case the maximum wind energy penetration in the NE region would reach 50.3% with negligible (less than 1%) surplus generation that would need to be curtailed or *exported*. The aggregate hourly wind power and net load during the month of October for scenario 3 can be observed in figure 17.

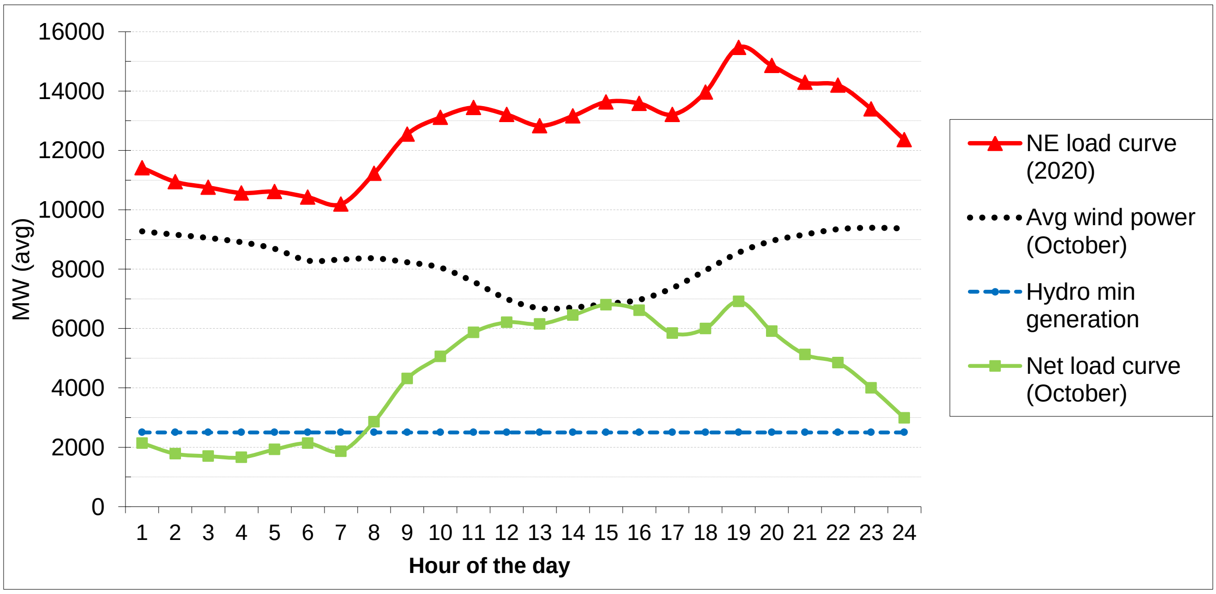

Figure 17: Average hourly load curve, aggregate diurnal wind power output, hydro minimum generation and net load curve in the NE during October for scenario 3.

Note, allowing up to 10% of electricity generation to be spilled or *exported* in scenario 3, would enable the maximum gross wind power penetration in the NE region to reach 71.8% with a capacity factor of 56.4%. In this scenario wind farms would still need to be built across 6 different cluster locations (see figure 18) because the maximum installation capacity per cluster is limited to 3000MW. The majority of wind farms would be installed in Bahia, while smaller amounts would be required in Ceará, Rio Grande do Norte and Paraíba.

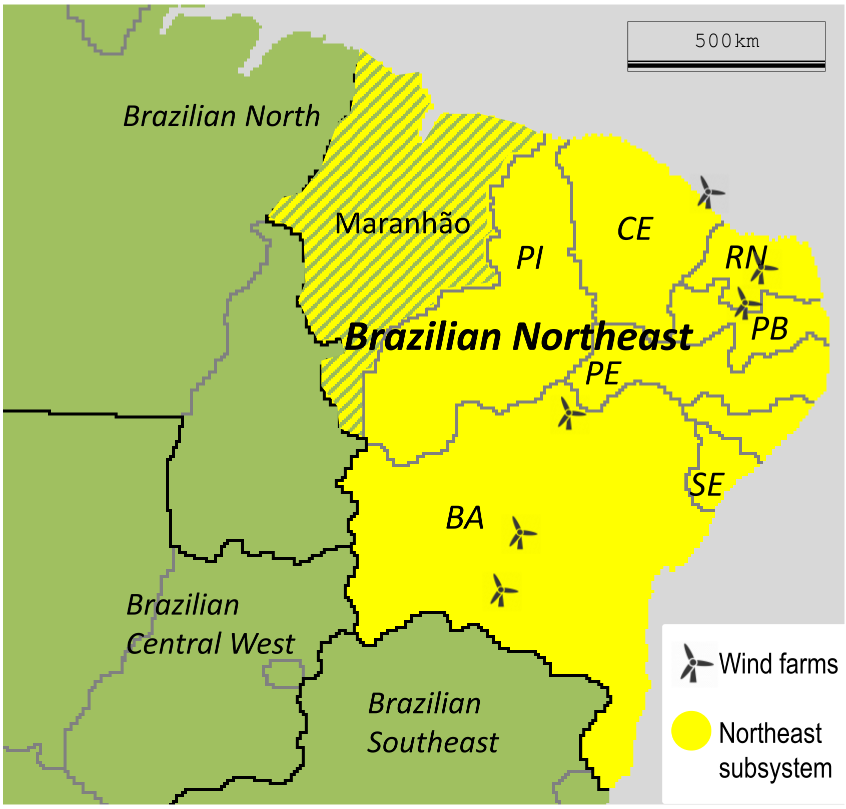

Figure 18: Location of the wind farm clusters in the Northeast region of Brazil for scenario 3.

It can be observed in figure 18 that the wind farm clusters with the highest annual capacity factors are typically located inland. Furthermore, wind farm clusters located inland, such as those in the state of Bahia, are all at elevations greater than 450m AMSL up to a maximum elevation of 1225m (see table 1). It can be observed in figure 17 that the average wind power output is significantly higher at night and before dawn than during daylight hours, which also confirms the influence of a nocturnal low level jet on the diurnal wind cycle over the interior plateaus of the Brazilian NE.

3.7. Comparing scenarios in terms of wind penetration, capacity factor and LCOE

In table 3 the 3 scenarios (baseline, scenario 2 and scenario 3) are compared in terms of maximum wind power penetration, corresponding wind power capacity factor and Levelised Cost of Electricity (LCOE). For each scenario, the maximum wind energy penetration was calculated with 5% of surplus generation permitted. In the baseline scenario a LCOE including externalities for wind power of $42.84/MWh was chosen as per the more expensive wind farm in the study by de Jong et al [10]. The wind power LCOE for scenarios 2 and 3 was then derived based on the wind power capacity factors of these respective scenarios.

Table 3: Comparison of wind power scenarios in terms of wind penetration, capacity factor and LCOE.

Wind power scenario	Tot. installed wind power	Gross wind penetration	Surplus energy	Capacity factor	Wind LCOE
	(MW)	(%)	(%)	(%)	($/MWh)
Baseline	16975	61.5%	5.0%	44.3%	42.84
Scenario 2	19692	68.2%	5.0%	42.4%	44.81
Scenario 3	13432	62.5%	5.0%	57.0%	33.32

While scenario 2 has a similar LCOE to the baseline, scenario 3 (which optimised the wind power capacity factor) had a LCOE 22% lower than the baseline scenario. The overall wind power capacity factors in the baseline scenario and scenario 2 were 44.3% and 42.4%, respectively, while in scenario 3 it was 57%. Therefore, to achieve 61.5% gross wind energy penetration in the baseline scenario would require approximately 16975MW of installed wind power, while for scenario 3 only 13432MW of installed wind power would be required for a gross penetration of 62.5%. The particular characteristics of optimisation scenarios 2 and 3 are used to demonstrate the importance of the average diurnal and seasonal cycles of wind power generation for different locations of wind farms within the same balancing area of a power system. For instance, most of the wind farm locations that best match the daily load curve, such as those located along the coast of Rio Grande do Norte, tend to have a lower capacity factor than wind farms located in the interior of the Brazilian NE, such as those in Bahia. Therefore, if the aim is to maximise wind energy penetration in the NE, then the large majority of wind farms should be built in the states of Rio Grande do Norte, Pernambuco and Sergipe. On the other hand, if the principal aim is to maximise capacity factors and minimise LCOE, then wind farms should mostly be installed in the interior of Bahia, even though in that state wind power tends to be strongest late at night and during the early hours of the morning.

However, it should be noted that the location of wind farms also depends on other factors, such as ease of accessibility for construction, terrain type, land availability and the proximity to transmission lines with spare capacity. In the auction process for contracting new wind farms in Brazil, regulations require wind energy companies to concurrently build wind farms together with their respective transmission links within the contract timeframe. Indeed, there are still undeveloped areas with excellent wind power potential, particularly in Bahia, however, to date these have not been contracted because of inaccessibility, or due to lack of sufficient transmission capacity in the vicinity. As a result, the baseline scenario, which considers all wind farms already constructed, under construction or contracted for construction, best approximates the future deployment of wind power in the NE region.

4. CONCLUSION

It was found that with 100% grid flexibility, wind energy in the NE region could generate up to 63% of the load before significant amounts of energy would need to be curtailed or *exported* to other Brazilian regions. However, with a grid flexibility of only 80% which reflects the minimum generation limits of hydroelectricity in the region, maximum gross wind energy penetrations would be approximately 50%, 62% and 71% with 1%, 5% and 10% of energy needing to be curtailed or *exported*, respectively. The NE electricity grid is able to effectively integrate more wind energy than in less flexible baseload dominated power systems, such as those simulated in the USA that are typically limited to wind penetrations of approximately 30% before curtailment becomes quite substantial [7, 8, 23]. Therefore, the results in this study show that having greater proportions of flexible generation in a balancing area is very important in minimising wind energy curtailment, which is in accordance with the findings of [7, 8] and [37]. Furthermore, the consistency of wind speeds and less seasonal variability of wind energy in the NE region is also a factor which will enable the region to have higher wind penetrations than in other balancing areas.

In addition, large scale solar PV could help diversify the generation matrix in the interior of the NE region and could be particularly complementary to the diurnal wind power profile in Bahia. Similar to the conclusions of [9, 26] and [58], the results in this study confirm that electricity demand in a large interconnected balancing area could be viably supplied from 100% renewable generation. This study also confirmed that seasonal patterns of wind power production in the NE are complementary to hydroelectric resource availability in the São Francisco basin. Therefore, wind power will improve energy security and save water in the NE reservoirs. This is particularly important because, in the long-term, average rainfall in the São Francisco and Amazon basins is predicted to markedly decrease, as a result of climate change. Therefore, rather than supplying base-load, hydroelectric resources will progressively be used for balancing the short term fluctuations of wind power and programmed to follow variations in the net load.

This work can be used as a basis to better enable system operators to plan for the large amount of wind energy expected to be integrated into the Brazilian Northeast's electricity system during the coming decade and a similar methodology could be used for other balancing regions. While the installed capacity of wind farms contracted for construction in the Northeast until 2020 is already known, the diurnal and seasonal generation from these wind farms is relatively unknown. Numerical weather prediction simulations, such as those performed here with the WRF model, can be used to predict hourly, daily and seasonal wind power production of wind farms that have already been installed or that will be installed in the future. Therefore, the provisional wind power generation, for example in 2020, can be simulated for a particular municipality, a state or across an entire balancing area such as the Northeast region.

The results of this work will also give an indication of where the region's transmission infrastructure will need to be upgraded to allow for interstate balancing and *exportation* of wind energy to other Brazilian regions in order to avoid curtailment of excess wind energy. Considering that by 2020 wind penetration in the NE region is projected to reach 57%, it is estimated that the maximum amount of instantaneous power that would need to be *exported* to other Brazilian regions to prevent unnecessary curtailment would be approximately 4150MW. Given that the transmission lines interconnecting the NE subsystem to the Brazilian Southeast already have sufficient capacity to transfer this amount of energy, it is envisaged that the Southeast region (which has a much larger electricity load) could import this surplus generation.

Nevertheless, in the last few years, several wind farms have been commissioned in the NE region, but in some cases, the construction of necessary transmission infrastructure needed to connect the wind farms to the grid has been delayed by more than 12 months. Given the rapid growth of wind power in the NE region, it is important that transmission lines and substations are planned and constructed in conjunction with new wind farms, so unnecessary energy losses can be avoided. Future research on wind power integration in the region could include modelling the planned transmission system in order to estimate any transmission constraints and the costs to rectify them. Additionally, the maximum ramp rates of the flexible part of the generation matrix could be analysed and simulated in order to determine how the power system in 2020 will deal with weather induced fluctuations in the net load. It would also be valuable to investigate the most economically viable solution amongst curtailment, inter-region transmission and energy storage for different amounts of surplus energy from variable renewables.

With further research the WRF model or BRAMS could be used to implement accurate weather forecasting, and predict wind speeds and *sub*-hourly wind power generation in the Brazilian NE. It should be noted that numerical weather predictions, such as the WRF model and BRAMS, have a degree of uncertainty which increases with higher temporal resolutions, so reducing the resolution to less than half-hourly intervals may be counterproductive. Nevertheless, these weather prediction tools could improve power system planning to better enable system balancing and scheduling of hydroelectric and gas plants to follow the net load curve and thereby minimise energy losses.

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6. REFERENCES

[1] Scorah H, Sopinka A, Van Kooten G C. The economics of storage, transmission and drought: integrating variable wind power into spatially separated electricity grids. Energy Economics 2012; 34: 536–541.

[2] REN21 - Renewable Energy Policy Network for the 21st Century. Renewables 2016 Global Status Report. Paris; 2016. Available at: http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report_REN21.pdf accessed on 14/09/2016.

[3] The Australia Institute, Pitt & Sherry. National Electricity Market update, data to June 2016. Carbon Emissions Index (CEDEX®), 2016. Available at: http://www.tai.org.au/sites/defualt/files/CEDEX%20Electricity%20update%20July%202016.pdf accessed on 14/09/2016.

[4] ANEEL – Agência Nacional da Energia Elétrica / Brazilian National Electricity Agency, BIG – Banco de Informações de Geração / Information Bank of Generation; 2016. Available at: http://www2.aneel.gov.br/area.cfm?idArea=15 accessed on 04/05/2016.

[5] Mai T, Wiser R, Sandor D, Brinkman G, Heath G, Denholm P, Hostick D J, Darghouth N, Schlosser A, Strzepek K. Exploration of High-Penetration Renewable Electricity Futures. Vol. 1 of Renewable Electricity Futures Study. NREL/TP-6A20-52409-1. Golden, CO: National Renewable Energy Laboratory. (2012).

[6] Lund P D, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures

to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews 2015; 45: 785–807.

[7] Nikolakakis T, Fthenakis V. The optimum mix of electricity from wind- and solar-sources in conventional power systems: Evaluating the case for New York State. Energy Policy 2011; 39: 6972–6980.

[8] Denholm P, Hand M. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy 2011; 39: 1817–1830.

[9] de Jong P, Kiperstok A, Sanchez A S, Dargaville R, Torres E A. Integrating large scale wind power into the electricity grid in the Northeast of Brazil. Energy 2016; 100: 401-415.

[10] de Jong P, Kiperstok A, Torres E A. Economic and environmental analysis of electricity generation technologies in Brazil. Renewable and Sustainable Energy Reviews 2015; 52: 725–739.

[11] CCEE - Câmara de Comercialização de Energia Elétrica / Brazilian Chamber of Electricity Trading. Info leilão / Auction info. 2015. Available at: www.ccee.org.br accessed on 04/05/2016.

[12] de Jong P, Sánchez A S, Esquerre K, Kalid R A, Torres E A. Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the Northeast region of Brazil. Renewable and Sustainable Energy Reviews 2013; 23: 526–535.

[13] Marengo J A. Water and Climate Change. Estudos avançados 2008; 22: 63.

[14] ONS – Operador Nacional do Sistema Elétrico. Históricas da Operação - Geração de Energia / History of Operation - Power Generation; 2017. Available at: http://www.ons.org.br/historico/geracao_energia.aspx accessed on 30/01/2017.

[15] Tanajura C A S, Genz F, Araujo H. Mudanças climáticas e recursos hídricos na Bahia: validação da simulação do clima presente do HadRM3P e comparação com os cenários A2 e B2 para 2070-2100 / Climate change and water resources in Bahia: validation of the HadRM3P current climate simulation and comparison with the A2 and B2 scenarios for 2070-2100. Revista Brasileira de Meteorologia ed. online; 2010. vol. 3. p. 345-58. Available at: http://repositorio.ufba.br/ri/handle/ri/3164 Accessed on 16/01/2016.

[16] Lucena A F P De, Szklo A S, Schaeffer R, Souza R R De, Borba B S M C, Costa I V L Da, Júnior A O P, Cunha S H F da, The vulnerability of renewable energy to climate change in Brazil. Energy Policy 2009; 37: 879-889.

[17] Marengo J A, Chou S C, Kay G, Alves L M, Pesquero J F, Soares W R, et al. Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. Climate Dynamics 2012; 38: 1829–1848.

[18] Lucena A F P, Szklo A S, Schaeffer R, Dutra R M. The vulnerability of wind power to climate change in Brazil. Renewable Energy 2010; 35: 904-12.

[19] Schubert C. Atlas Eólico / Wind Power Atlas: Bahia. SECTI, SEINFRA, CIMATEC/ SENAI, Salvador, 2013.

[20] Schubert C, Brower M, Sá A L de, Zack J. Atlas do Potencial Eólico Brasileiro / Atlas of

Brazilian Wind Power Potential, 2001.

[21] Tory K, Ye H, Dare R. Tropical cyclone detections and seasonal genesis variables in ECMWF reanalysis data. 32nd Conference on Hurricanes and Tropical Meteorology – American Meteorological Society; 2016.

[22] ONS – Operador Nacional do Sistema Elétrico, Boletim Mensal de Geração Eólica - Dezembro, 2015 / 2016 / Wind Generation Monthly Bulletin - December, 2014/ 2015/ 2016. Available at: http://www.ons.org.br/resultados_operacao/boletim_mensal_geracao_eolica/index.aspx accessed on 20/01/2017.

[23] Eichman J D, Mueller F, Tarroja B, Schell L S, Samuelsen S. Exploration of the integration of renewable resources into California's electric system using the Holistic Grid Resource Integration and Deployment (HiGRID) tool. Energy 2013; 50: 353–363.

[24] Rife D L, Pinto J O, Monaghan A J, Davis C A, Hannan J R. Global Distribution and Characteristics of Diurnally Varying Low-Level Jets. American Meteorological Society - Journal of Climate 2010; vol 23: no. 19; 5041–5064.

[25] Schmidt J, Cancella R, Pereira A O Jr. The effect of windpower on long-term variability of combined hydro-wind resources: The case of Brazil. Renewable and Sustainable Energy Reviews 2016; 55: 131–141.

[26] Mason I G, Page S C, Williamson A G. Security of supply, energy spillage control and peaking options within a 100% renewable electricity system for New Zealand. Energy Policy 2013; 60: 324–333.

[27] Carvalho D, Rocha A, Gómez-Gesteira M, Santos C. A sensitivity study of the WRF model in wind simulation for an area of high wind energy. Environmental Modelling & Software 2012; 33: 23–34.

[28] Carvalho D, Rocha A, Gómez-Gesteira M, Santos C. WRF wind simulation and wind energy production estimates forced by different reanalyses: Comparison with observed data for Portugal. Applied Energy 2014; 117: 116–126.

[29] Draxl C, Hahmann A N, Peña A, Giebel G. Evaluating winds and vertical wind shear from Weather Research and Forecasting model forecasts using seven planetary boundary layer schemes. Wind Energy 2014; 17:39–55.

[30] Ramos D N S, Lyra R F F, Silva Junior R S. Previsão do vento utilizando o modelo atmosférico WRF para o estado de Alagoas / Wind prediction using the WRF model in the state of Alagoas, Brazil. Revista Brasileira de Meteorologia 2013; vol 28: no. 2; 163–172

[31] Pinto L I C, Martins F R, Pereira E B, Fisch G F, Lyra R F F. Confiabilidade nas estimativas do regime do vento fornecidas pelo BRAMS no estado de Alagoas: influência do aninhamento e da resolução horizontal de grades / Reliability evaluation of wind regime estimates provided by the BRAMS model for the state of Alagoas, Brazil: influence of nesting and horizontal resolution grids. Revista Brasileira de Meteorologia 2014; vol 29: no. 2; 242-258.

[32] Oliveira S S. Análise do potencial eólico do estado da Paraíba utilizando modelos de mesoescala / Analysis of wind power potential in the state of Paraíba using mesoscale models. Tese (Doutorado em Meteorologia) - Universidade Federal de Campina Grande; 2013.

[33] Tuchtenhagen P, Basso J, Yamasaki Y. Avaliação do potencial eólico no Brasil em 2011 / Wind power assessment over Brazil in 2011. Ciência e Natura, Santa Maria 2014; vol. 36 Ed. Especial II; 390–401.

[34] Miranda R, Soria R, Schaeffer R, Szklo A, Saporta L. Contributions to the analysis of “Integrating large scale wind power into the electricity grid in the Northeast of Brazil” [Energy 100 (2016) 401-415]. Energy 2017; 118: 1198–1209.

[35] EPE - Empresa de Pesquisa Energética. Estudos de planejamento da expansão da geração - Empreendimentos eólicos / Planning studies of generation expansion - Wind power developments. Ministério de Minas e Energia / Brazilian Ministry of mines and energy, 2016. Available at: http://www.epe.gov.br/geracao/Documents/EPE-DEE-RE-107%202016.pdf accessed on 18/12/2016.

[36] Wang Q, Wu H, Florita A R, Martinez-Anido C B, Hodge B M. The value of improved wind power forecasting: Grid flexibility quantification, ramp capability analysis, and impacts of electricity market operation timescales. Applied Energy 2016; 184: 696–713.

[37] Waite M, Modi V. Modeling wind power curtailment with increased capacity in a regional electricity grid supplying a dense urban demand. Applied Energy 2016; 183: 299–317.

[38] Zhao H, Wu Q, Hu S, Xu H, Rasmussen C N. Review of energy storage system for wind power integration support. Applied Energy 2015; 137: 545–53.

[39] Zhang N, Hu Z, Shen B, Dang S, Zhang J, Zhou Y. A source–grid–load coordinated power planning model considering the integration of wind power generation. Applied Energy 2016; 168: 13–24.

[40] Welsch M, Deane P, Howells M, _O Gallachoir B, Rogan F, Bazilian M, et al. Incorporating flexibility requirements into long-term energy system models - A case study on high levels of renewable electricity penetration in Ireland. Applied Energy 2014; 135: 600–15.

[41] Deane J P, Drayton G,_Ó Gallachóir B P. The impact of sub-hourly modelling in power systems with significant levels of renewable generation. Applied Energy 2014; 113: 152-158.

[42] WRF - Weather Research and Forecasting Model webpage. Available at: http://www.wrf-model.org/index.php accessed on 06/02/2016.

[43] University of Wyoming, Department of Atmospheric Science. Surface Observations for Fortaleza Pinto Mar, Brazil, 2014. Available at: http://weather.uwyo.edu/surface/meteorogram/ accessed on 01/03/2016.

[44] WIND-TURBINE-MODELS. Alstom ECO 86 (Turbine) / Alstom Ecotècnia ECO 80/2000 (Turbine) / Alstom Ecotècnia ECO 74/1670 (Turbine). Wind-Turbine-Models.com, 2013. Available at: http://en.wind-turbine-models.com/turbines?manufacturer=116 and http://en.wind-turbine-models.com/turbines?manufacturer=53 accessed on 20/07/2016.

[45] ALSTOM. ECO 80 Platform - ECO 80 & ECO 86 Wind Turbines. Alstom Wind Power Solutions, 2010.

[46] ONS – Operador Nacional do Sistema Elétrico, Boletim Mensal de Geração Eólica - Janeiro/ Fevereiro / Março / Abril / Maio / Junho / Julho / Agosto / Setembro / Outubro / Novembro / Dezembro, 2014 / Wind Generation Monthly Bulletin - January / February / March / April / May / June / July / August / September / October / November / December, 2014a. Available

at: http://www.ons.org.br/resultados_operacao/boletim_mensal_geracao_eolica/index.aspx accessed on 16/07/2015.

[47] ONS – Operador Nacional do Sistema Elétrico / Brazilian National Electricity System Operator. RE-3-128-2008 PEL 2009-2010; 2008.

[48] ONS – Operador Nacional do Sistema Elétrico. 2ª Revisão Quadrimestral das Projeções da demanda de energia elétrica do Sistema Interligado Nacional 2014-2018 / 2nd Quarterly Review of Projections of electricity demand of the National Interconnected System 2014-2018. EPE - Empresa Pesquisa Energética/ONS; 2014b.

[49] Ulbig A, Andersson G. Analyzing operational flexibility of electric power systems. Electrical Power and Energy Systems 2015; 72: 155–164.

[50] De Jonghe C, Delarue E, Belmans R, D'haeseleer W. Determining optimal electricity technology mix with high level of wind power penetration. Applied Energy 2011; 88: 2231–2238.

[51] Batas Bjelić I, Rajaković N, Ćosić B, Duić N. Increasing wind power penetration into the existing Serbian energy system. Energy 2013; 57: 30–37.

[52] François B, Borga M, Anquetin S, Creutin JD, Engeland K, Favre AC, et al. Integrating hydropower and intermittent climate-related renewable energies: a call for hydrology. Hydrological Processes 2014; 28: 5465-8.

[53] Acker T L, Robitaille A, Holttinen H, Piekutowski M, John Olav Giæver Tande J O G. Integration of wind and hydropower systems: Results of IEA wind task 24. Wind Engineering 2012; v 36, n 1, p 1-18.

[54] ONS – Operador Nacional do Sistema Elétrico. Representação das defluências das usinas do Rio São Francisco nos estudos de planejamento e programação da operação. Notícias 01/11/2016; 2016. Available at: http://www.ons.org.br/sala_imprensa/2016nov01-defluencia_saofrancisco.aspx Accessed on 21/11/2016.

[55] ONS – Operador Nacional do Sistema Elétrico. Plano da Operação Energética – PEN 2012 VOL. I – Relatório executivo RE 3/0146/2012; 2011. Available at: http://www.ons.org.br/download/avaliacao_condicao/operacao_energetica/PEN%202012_VOL1_RELATORIO%20EXECUTIVO.pdf Accessed on 16/01/2016.

[56] AEMO - Australian Energy Market Operator. 100 per cent renewables study – modelling outcomes. AEMO, 2013b. Available at: http://www.environment.gov.au/climate-change/publica<ons/aemo-modelling-outcome accessed on 23/08/2015.

[57] Drouineau M, Maïzi N, Mazauric V. Impacts of intermittent sources on the quality of power supply: The key role of reliability indicators. Applied Energy 2014; 116: 333–343.

[58] Elliston B, Macgill I, Diesendorf M. Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market. Renewable Energy 2014; 66: 196–204.

[59] Pereira E B, Martins F R, Pes M P, da Cruz Segundo E I, Lyra A A. The impacts of global climate changes on the wind power density in Brazil. Renewable Energy 2013; 49: 107-110.

[60] Alliance for Water Efficiency. Irrigation Scheduling Introduction, 2016. Available at:

http://www.allianceforwaterefficiency.org/Irrigation_Scheduling_Introduction.aspx Accessed on 26/01/2017.

[61] ONS – Operador Nacional do Sistema Elétrico / Brazilian National Electricity System: Apresentações Programa Mensal da Operação Energética (PMO). PMO de setembro de 2016 - Nota Executiva GPO/GPO2/087//2016 & PMO de julho de 2016 - Nota Executiva GPO/GPO2/068//2016; 2016. Available at: http://www.ons.org.br/operacao/apresentacoesPMO.aspx accessed on 16/01/2017.

[62] Hunt J D, Marcos Freitas M A V, Junior A O P. Enhanced-Pumped-Storage: Combining pumped-storage in a yearly storage cycle with dams in cascade in Brazil. Energy 2014; 78: 513–523.

CHAPTER 5

The impact of wind power and PV integration on the stability of the grid

The impact of wind power and PV integration on the stability of the grid

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ABSTRACT

Solar and wind energy are contributing ever greater proportions of utility scale generation. However due to the intermittent nature of wind power and solar PV, there are limits to the penetration of these technologies. This paper examines the challenges of balancing solar and wind power with the electricity demand from the grid. A literature review is conducted on the impact that these renewable sources have on the stability and quality of a power system, together with the most common solutions available to mitigate power quality problems. The second part of this paper investigates the effects of large scale PV and wind integration on the Australian national electricity market and the findings of the Australian Energy Market Operator (AEMO) are reviewed. The advantages of integrating wind farms in power systems which have significant hydroelectric generation, such as in Tasmania and Brazil, are also examined. Finally, the benefits of implementing pumped hydro storage for stockpiling excess wind energy are evaluated. It is concluded that this type of dedicated storage is only necessary in power systems with large amounts of inflexible base-load thermal generation where surplus wind energy cannot be absorbed or easily exported.

Keywords: Renewable Energy; Wind Power; Solar; Hydroelectricity; Integration; 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. Wind power at good locations in Australia is already more cost effective than building a new coal-fired power station. In Brazil wind power is second only to large scale hydroelectricity in terms of levelised cost of electricity (DE JONG, 2013 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 amount of wind and solar resources available, but rather the smooth 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 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. Various modelling tools already exist designed to simulate and/or optimise a power system in order to maximize profits and/or maximise renewable penetration at least cost. Some of the more well-known tools include: PLEXOS Integrated Energy Model, SAM (System Advisor Model), NEMO (National Electricity Market Optimiser), GENESYS (Genetic Optimisation of a European Energy Supply System), MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), MUREIL (Melbourne University Renewable Energy Integration Laboratory), NEWAVE and HOMER (Hybrid Optimization Model for Electric Renewables), etc. However, these tools typically do not address the impacts that variable renewable energy generation has on grid stability and power quality.

The 2nd section of this paper reviews the challenges of integrating solar and wind energy into the electricity grid and the impact of these generation technologies on power quality and grid stability. In section 3, the strategies implemented by the Australian Energy Market Operator (AEMO) to integrate large scale PV and wind energy are reviewed. This section of the paper outlines the advantages and challengers of integrating wind energy into Tasmania's electricity grid which has a high proportion of hydroelectricity. Section 4 of this paper reviews pumped hydro and other storage technologies as a means to utilising excess wind energy. Finally, a summary of the main issues in Australia on large scale wind power and solar PV integration are presented in the conclusion.

2. REVIEW OF RENEWABLE ENERGY INTEGRATION STUDIES

Studies by Sinden (2007) and Hoicka & Rowlands (2011) found that increasing the number of renewable energy sources such as wind and solar power across various geographical locations significantly smoothed out power generation and produced less variability. In figure 1, AEMO (2013a) demonstrated that the aggregate wind generation output, within South Australia, changes less over a five-minute period than the output of a single wind farm.

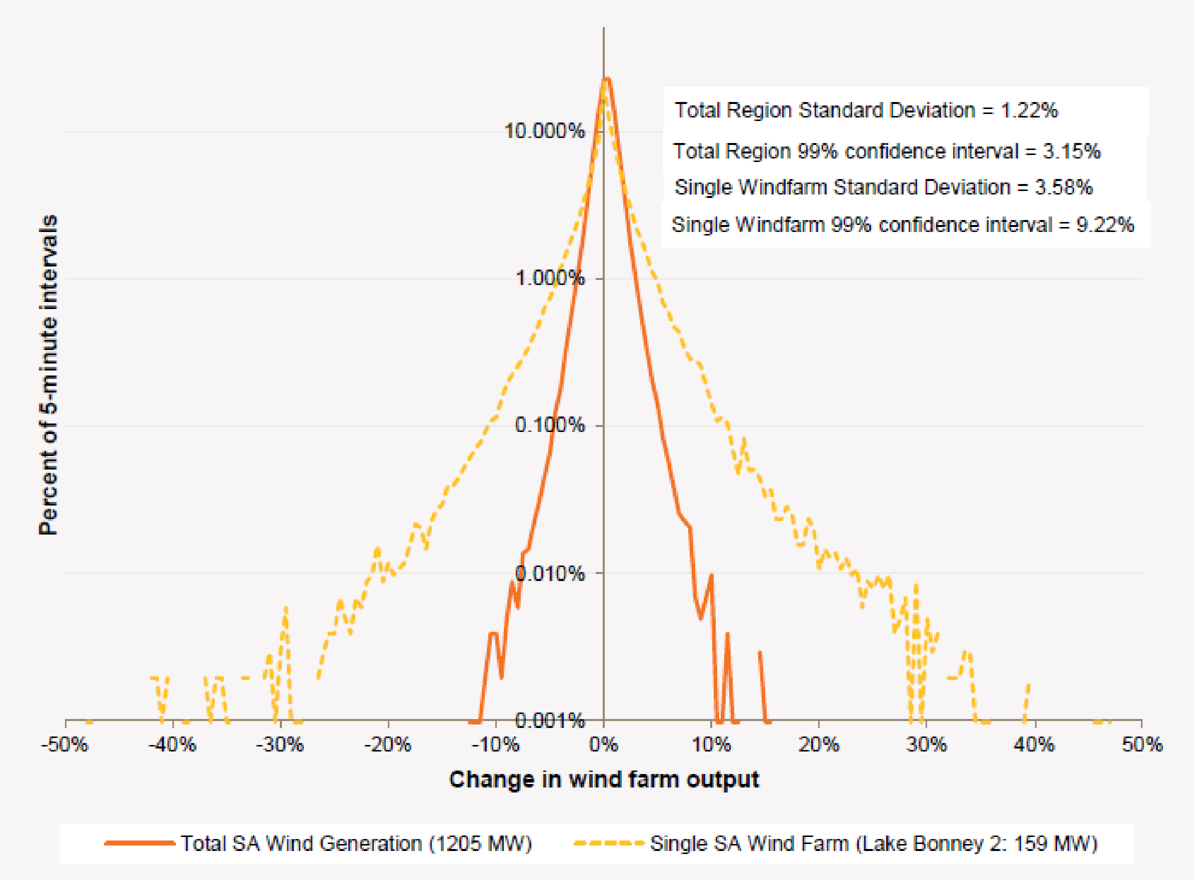

Figure 1: Distribution of five-minute changes in South Australian wind generation (as a percentage of installed capacity) during 2012–13. Source: AEMO (2013a).

The 99% confidence level for a five-minute change across all Australian installed wind generation is only 2.13%. This is important because five-minute balancing arrangements are used by AEMO for frequency control, and AEMO (2013a) conclude that even the impact of 2020 wind generation levels should remain manageable within the existing frequency regulation arrangements.

In addition to the effect of renewable energy intermittence on power system balancing, there are several challenges that can affect power quality. Shafiullah et al (2010) investigate potential challenges of integrating renewable energy into the grid including voltage and frequency fluctuations, power system transients and harmonics, reactive power, synchronization, long transmission lines, low power factor, storage systems, load management, and forecasting and scheduling.

Voltage fluctuation, also known as voltage flicker can be an issue for wind and solar energy due to their intermittency (LIBAO et al, 2011 and SHAFIULLAH et al, 2010). Voltage fluctuation is quantified by the short term flicker severity measurement for a particular grid (SHAFIULLAH et al, 2010).

Power electronics devices, such as inverters used with solar PV systems and some wind turbines can inject harmonics into the grid and this may create voltage distortion problems. However, harmonic distortion can be minimized by control systems and special filters to keep any distortion within acceptable limits (SHAFIULLAH et al, 2010). Induction generators (used in some wind turbines) consume reactive power. To avoid power quality problem in the grid, induction generators require reactive power compensation. Power compensation can be achieved by using fixed or switched capacitors, or alternatively static compensators, which are described in more detail by Hossain (2012). The synchronisation of wind farms with the grid frequency is another important issue for renewable energy integration. Specifically, the frequency, terminal voltage, phase-sequence and phase angle of wind power should match as closely as possible with that of the grid (SHAFIULLAH et al, 2010).

According to Shafiullah et al (2010), mismatches between renewable energy output and grid load may lead to energy wastage. Therefore accurate forecasting of renewable resources combined with scheduling and load management systems are essential for the efficient operation of a smart power grid. Therefore, the study by Shafiullah et al (2010) developed forecasting models to predict the daily distribution of solar irradiation and hourly distribution of wind speed using common regression algorithms. The different algorithms were ranked in terms of their performance to determine the most suitable to accurately forecast solar irradiation and wind speed.

Similarly, Libao et al (2011) review various papers examining the potential challenges, including frequency and voltage fluctuations that smart grids may face due to large scale wind generation. Tamimi et al (2010), investigate the maximum optimal wind penetration level of multiple new wind farms in a power system. Using an iterative process, the size of wind farms is incremented until different voltage stability margin limits are reached. Luo et al (2007) estimated the optimal wind power penetration level to be 49%. In the future, as wind penetration increases, aspects of power system operation, stability and control will need to be addressed. Some possible solutions include “green” demand management, smart device development, IT technology to monitor and control the grid in real time, and energy storage systems (LIBAO et al, 2011).

Tröster et al (2010) discuss the impact of a high proportion of renewable energy sources, such as wind power, on the future European transmission system. The two main reasons for curtailed renewable energy are a shortage of demand at times of excess generation capacity or a lack of transmission capacity to transfer energy to where there is demand. The North Sea offshore wind capacity is predicted to reach 60GW by 2030 and therefore, the HVDC transmission links between the North Sea, Norway and Great Britain would need to be reinforced (TRÖSTER et al, 2010). These transmission links would be very expensive, therefore an evaluation needs to be conducted comparing the overall lifecycle cost of a network designed to give precedence to local generation that incurs some curtailment, versus the cost of transmission upgrades required to minimise wind power curtailment. The aim of this economic evaluation is to determine the minimum grid upgrade cost that would result in minimum energy curtailment (TRÖSTER et al, 2010).

Large scale penetration of wind power can also affect the stability and quality of a power system. The European Wind Energy Association predicts that installed wind power capacity in Europe will reach 230 GW by 2020 and 300 GW by 2030 (HOSSAIN et al, 2012). According to Hossain et al (2012), traditionally, a large proportion of wind farms use fixed-speed wind turbines (FSWTs) fitted out with induction generators. The main problem is that these induction generators consume reactive power and this can deteriorate the local grid voltage stability during system transient and fault contingencies. For example, during a short-circuit fault many induction generators can trip at the same time. A power system with a low proportion of synchronous generators can be susceptible to system imbalances or even collapse (HOSSAIN et al, 2012) and frequency control could be problematic especially during periods of low demand (AEMO, 2013b). To a certain degree, power factor and voltage regulation devices such as a static VAR (reactive power) compensator (SVC) and a static synchronous compensator (STATCOM) can be used in transmission networks with large scale wind power integration to improve voltage stability and control (HOSSAIN et al, 2012 and LIBAO et al, 2011). Additionally wind farms installed with low-voltage-ride-through (LVRT) capability allow for power systems to better withstand network disturbances. Nevertheless, according to AEMO (2013b) at least 15% of synchronous generation is required in a power system because the mechanical inertia of synchronous generators inherently provide some natural damping of frequency deviations.

The majority of modern wind farms use variable speed wind turbines fitted with doubly fed induction generators (DFIGs) which have reactive power and voltage control capabilities. They are able to operate at a given power factor by regulating reactive power and grid voltage, because they use advanced power electronic converters (HOSSAIN et al, 2012). DFIGs can even improve power system transient stability. However during fault conditions they are still susceptible because they cannot deliver enough reactive current compared to synchronous generators during deep voltage sags. DFIGs can be combined with compensation devices such as STATCOMs so that they exhibit similar behaviour and stability to synchronous generators (HOSSAIN et al, 2012). Variable speed wind turbines can also be fitted with synchronous generators, however, these types of generators are more complicated, more expensive and therefore, less commonly used.

According to Vilchez et al (2013), there has been a move away from centralized power generation toward distributed generation systems such as rooftop PV. As a result of distributed generators supplying the grid, unidirectional power flows are being reversed. The authors use a test network with differing configurations to examine power quality behaviour with increasing penetrations of renewable energy technologies. Vilchez et al (2013) found that voltage sag occurrences in the 380kV system marginally increased with larger penetrations of wind farms, but voltage sag actually decreased slightly with the integration of wind farms in the 110kV. However with increased amounts of distributed generation, such as solar PV and micro-turbines, there were significantly more voltage sag occurrences. Renewable energy systems can also be a source of voltage flicker. The study found that the short-term flicker severity level remained almost the same with the integration of wind farms. However with larger amounts of distributed generation, the short-term flicker severity increased up to a maximum of 1%. The flicker severity was dependent on the types of renewable energy technology and their position in the network (VILCHEZ et al, 2013). Finally, harmonic analysis of the network demonstrated that the percentage of Total Harmonic Distortion increased slightly with the integration of more wind energy and increased more markedly with integration of distributed generation resources into the 110kV transmission system. Nevertheless, even with up to 100% penetration in the network, the Total Harmonic Distortion remained within established grid limits (VILCHEZ et al, 2013). The authors conclude that the integration of renewable energy systems can even have a positive impact on network power quality, but this depends on the type, configuration and penetration level of renewable technologies connected to the network.

3. THE EFFECT OF LARGE SCALE PV AND WIND INTEGRATION ON THE AUSTRALIAN ELECTRICITY GRID

According to the AEMO (2013a) report, utility-scale PV generation in Australia will exceed 1000MW by 2020 and will be required to participate in the central dispatch process. To enable improved scheduling and dispatch of generation sources in conjunction with PV, AEMO is developing an Australian Solar Energy Forecasting System. Nevertheless, at these low levels of penetration, utility-scale PV is not expected to impact on the power system frequency and quality. However, if grid connected utility-scale PV systems of several hundred MW are installed within a very small geographic region, then output fluctuations from the PV systems, due to rapid cloud shadowing, could impact on the power system frequency and voltage control (AEMO, 2013a). Due to its distributed nature, AEMO considers rooftop PV systems, which total more than 4500MW of installed capacity (APVI, 2016), as a reduction in net load rather than as a source of supply. According to AEMO (2013a) the increase in demand, above the base load, during daylight hours is higher than the total capacity of PV generation. Currently PV electricity production only accounts for 2.8% of total consumption in Australia (APVI, 2016).

The AEMO (2013a) report predicts that grid connected wind generation capacity in Australia will reach 11.5GW by 2020 and this will displace conventional synchronous generation which could result in power system inertia being reduced. Power system frequency control in Victoria, New South Wales and Queensland will not be significantly affected, however, power system operators will need to make changes in Tasmania and South Australia to ensure ongoing control of the system frequency within required limits, particularly following contingency events. During low demand and high wind periods in Tasmania, power system fault currents could fall below the required levels, for example, to maintain Basslink transfers (AEMO, 2013a and ACKERMANN, 2011). According to AEMO (2013a), by 2020, approximately 5,750GWh (35%) and 1,260 GWh(15%) of potential wind energy generation in Victoria and South Australia, respectively, could be curtailed due to network limitations.

To some degree, AEMO could manage the impacts on power system frequency and quality with existing processes by using constraint equations in the central dispatch process to limit wind generation. Alternatively, existing systems, processes and control schemes could be augmented or modified to assist in the integration of variable renewable generation. For example, new frequency control ancillary service requirements could be established to allow adequate control under low power system inertia conditions. Purpose-built synchronous condensers could be installed to maintain system inertia and power system fault levels. Alternatively, existing generating units could be modified to operate either with a reduced minimum load or as synchronous condensers (AEMO, 2013a).

This last technique to address the impact of wind power could be implemented in Tasmania at low cost, due to the large hydroelectric capacity in the state. Additionally, Tasmania has some of the most reliable wind conditions for wind generation in the world and existing wind farms have average capacity factors above 40% (MOSADEGHY et al, 2013 and AEMO, 2013a). Mosadeghy et al (2013) found that coordinating a small proportion of the output from Tasmanian hydroelectric plants with wind farms can balance wind power fluctuations and also significantly increase the load carrying capability (or capacity value) of wind farms in Tasmania.

Piekutowski et al (2012) argue that large scale wind penetration in Tasmania could reduce system inertia and therefore significantly increase Frequency Control Ancillary Services (FCAS) requirements, as well as decrease system fault levels. Due to its inherent dynamic response and energy storage capabilities, existing hydroelectric generation in Tasmania could be complementary to large scale wind power operation. However, according to Piekutowski et al (2012), Tasmania may not have enough fast FCAS as wind penetration levels increase, particularly during high wind periods. This is because hydroelectric plants have limited governor response capabilities in short time frames (e.g. 6 seconds) which are required for fast FCAS. An number of options have been proposed to improve the delivery of fast FCAS including, increasing system inertia by running some hydroelectric generators as synchronous condensers, implementing tail water depression (TWD) mode (that is, enabling fast transition from synchronous condenser mode to generation), and/or increase guide vane opening rates (PIEKUTOWSKI et al, 2012).

The predicted high wind energy penetration in Tasmania will require more active and frequent net load balancing from hydro plants which will most likely increase the number of start-stop operations, low-load running and thermal load cycling of some hydroelectric turbines. This could reduce the normal lifetime of hydroelectric generator components as a result of more wear and tear, and increase maintenance costs (PIEKUTOWSKI et al, 2012). However, slight modifications can be made to existing hydroelectric plants in order to improve their fast FCAS response capabilities and reduced water inefficiencies at the same time. These modifications would be significantly cheaper than alternative measures, such as installing new ancillary services or energy storage systems. However, market regulations need to improve to enable more recognition of services which can better enable wind power integration. This would encourage the necessary modifications to be made to hydroelectric plants and facilitate cost recovery (PIEKUTOWSKI et al, 2012).

Australian case studies found that a high proportion of wind power capacity (up to 1,300MW or 33%) could be integrated into the Tasmanian generation mix, provided the HVDC interconnect with the Australian mainland is utilized and measures are taken to improve system inertia and power system fault levels (ACKER et al, 2012). Moreover, extra hydroelectric generators operating as synchronous condensers or in tail water depression mode could reduce low system inertia and improve the integration of the wind generation in Tasmania (ACKER et al, 2012 and PIEKUTOWSKI et al, 2012). However, without the Basslink interconnect to the mainland, hydroelectric storage is unable to absorb all output from large scale wind generation due to the coincident of high winds with high inflows.

Large scale wind power integration will incur additional costs due to enhanced system balancing requirements, however, the overall cost of electricity may decrease as a result of wind energy displacing higher cost generation (ACKER et al, 2012). Large balancing areas with good transmission interconnections can more easily integrate wind power with hydroelectricity. According to Acker et al (2012), above 20% penetration, changes in system operation, such as use of advanced wind forecasting, may be necessary to optimally integrate wind power with hydroelectric plants. Non-power constraints on hydroelectric dams, such as irrigation and environmental regulations, can reduce hydro system flexibility to balance wind power. However, these constraints generally occur on different time scales to those related to wind hydro integration (ACKER et al, 2012). The inherent flexibility of hydroelectric power stations together with their energy storage capabilities makes them ideally suited to integrate wind energy into the power system.

4. USING PUMPED HYDRO FOR EXCESS WIND ENERGY

Clearly the integration of large scale wind power into Tasmania’s power system can be achieved without the need to install new back up ancillary services or new dedicated storage systems. However, by 2020, 5,750GWh and 1,260GWh of annual wind generation in Victoria and South Australia, respectively, could be curtailed due to thermal power constraints, oversupply and interconnector export limitations between states (AEMO, 2013a). To some degree, this curtailed wind energy could be minimised by implementing demand side management. Another solution is to store the excess supply of wind energy with the aid of pumped hydro storage (PHS).

The global capacity of pumped hydro storage is estimated to be 140-150GW (REN21, 2014 and IRENA, 2015) and is projected to grow to 325GW by 2030 (IRENA, 2015). Given the existing quantity hydro-electric infrastructure already existing in Tasmania and Brazil this type of energy storage could be a very cost effective way to balance power from variable renewable resources. China and Japan already have 21.5GW and 26GW of installed pumped storage, respectively and this technology has an overall system efficiency of 80–90% (REN21, 2014). Other countries, such as Spain, Indonesia, Brazil and Iran also use PHS technology.

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. More recently, there have been studies in Germany, Norway and Greece on combining PHS with wind power to provide ancillary services, regulation and spinning reserve (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).

Similarly, Khatibi and Jazaeri (2008) examined how rejected energy can be applied to pump water from a lower reservoir to an upper reservoir and be re-utilized via a hydroelectric plant.

Endegnanew et al (2013) investigate the effects of combining offshore wind farms in the North Sea with pumped hydro storage in Norway. Two cases are simulated of power flow contingencies between Norway's pumped hydro plant and Continental Europe. 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 ±1Hz.

Australia already has 1.5GW of pumped hydro capacity located in NSW and Queensland, however, no new facilities have been installed for the last 30 years (HEARPS et al, 2014). A portion of this capacity will no doubt be used to balance future wind generation, however, these existing PHS facilities are located several hundred kilometres from future wind farms in Victoria and South Australia which purportedly will have a proportion of curtailed energy. Hearps et al (2014) investigate and analyse the economics of installing new seawater pump hydro energy storage facilities 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. Further work in this area needs to be undertaken in order to fully assess the feasibility and weigh the benefits of installing new pump hydro facilities of this type in Australia or alternatively retro-fitting existing freshwater dams.

Given the large quantity of conventional hydroelectric storage in Brazil, wind power (as well as biomass and solar 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, 2017). 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.

4.1. 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. 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) analyse 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. 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.

Díaz-González et al (2012) also review several energy storage technologies in terms of their main characteristics, operating principles, efficiency, capital cost per MWh and describe in detail their various applications to enable smooth integration of wind power into an electrical network. 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 CO2eq). 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 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. 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).

5. CONCLUSION

This study has reviewed a number of the obstacles related to the integration of large scale solar and wind energy into a regional power system. Variable renewable energy sources can impact on the power quality and stability of the grid, however, there are several methods and technologies already used in the field, such as STATCOM, SVC, LVRT and harmonic filters that address these issues.

It was found that AEMO could manage power system impacts with existing processes, however, by 2020 some wind generation would need to be curtailed. The integration of large scale wind power into Tasmania's power system can be achieved at relatively low cost by modifying existing hydroelectric plants, so they can better operate as ancillary services. On the other hand, without alterations to the Australian national grid, wind energy would need to be curtailed due to the oversupply of wind power in Victoria and South Australia. Nevertheless, if it proves economically viable, this excess energy could be utilised by implementing demand side management, improving the interconnector capacities between states or by installing new pumped hydro storage in Victoria and South Australia.

The flexibility of conventional hydroelectric storage in Brazil as well as existing regional interconnectors should enable the integration of large proportions of variable renewable energy, however, in the future PHS may be a viable alternative for storing surplus wind energy. As suggested by Tröster et al (2010), further research is necessary in order to determine the maximum proportion of surplus wind energy that can be economically utilized by the electricity grid at least cost. Furthermore, the lifecycle cost of wind energy curtailment needs to be weighed against the cost of demand side management, upgrading transmission links between states and also against the cost of installing PHS systems.

6. REFERENCES

Acker T L, Robitaille A, Holttinen H, Piekutowski M, John Olav Giæver Tande J O G. Integration of wind and hydropower systems: Results of IEA wind task 24. Wind Engineering 2012; v 36, n 1, p 1-18.

Ackermann T, Kuwahata R. Lessons learned from international Wind integration studies - AEMO wind integration WP4(A). Energynautics, Australian Energy Market Operator, 2011.

AEMO - Australian Energy Market Operator. Integrating renewable energy - Wind integration studies report for the National Electricity Market (NEM). AEMO, 2013a.

AEMO - Australian Energy Market Operator. 100 per cent renewables study – modelling outcomes. AEMO, 2013b. Available at: http://www.environment.gov.au/climate-change/publica<ons/aemo-modelling-outcome accessed on 23/08/2015.

APVI - Australian PV Institute. Warwick J, Renate E. National Survey Report of PV Power Applications in Australia, 2015. APVI, June 2016.

Canales F A, Beluco A, Mendes C A B. Usinas hidrelétricas reversíveis no Brasil e no mundo: aplicação e perspectivas / Pumped storage hydropower in Brazil and the world: application and perspectives. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental Santa Maria; 2015, vol. 19, no. 2: 1230-1249.

CCEE - Câmara de Comercialização de Energia Elétrica / Brazilian Chamber of Electricity Trading. Info leilão. 2014. Available at: www.ccee.org.br accessed on 06/09/2014.

de Jong P. Economic, technical and environmental analysis of renewable and non-renewable electricity generation technologies in Brazil. Master's Dissertation – Escola Politécnica, Universidade Federal da Bahia (UFBA), Salvador; 2013.

de Jong P, Kiperstok A, Sanchez A S, Dargaville R, Torres E A. Integrating large scale wind power into the electricity grid in the Northeast of Brazil. Energy 2016; 100: 401-415.

de Jong P, Dargaville R, Silver J, Utembe S, Kiperstok A. Torres E A. Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid. Applied Energy 2017; 195: 538–555.

Díaz-González F, Sumper A, Gomis-Bellmunt O, Villafáfila-Robles R. A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews 2012; 16: 2154–2171.

EIRGRID. All-Island Wind and Fuel Mix Report, 2014. Available at: http://www.eirgrid.com/operations/systemperformancedata/all-islandwindandfuelmixreport/ Accessed on 16/05/2015.

Endegnanew A G, Farahmand H, Huertas-Hernando D. Frequency Quality in the Nordic Power System: Wind Variability, Hydro Power Pump Storage and Usage of HVDC Links. Energy Procedia 2013; 35: 62 – 68.

GWEC - Global Wind Energy Council. Global Wind Report Annual Market Update 2014, 2015.

Hearps P, Dargaville R, McConnell D, Sandiford M, Forcey T, Seligman P. Opportunities for Pumped Hydro Energy Storage in Australia. Arup / Melbourne Energy Institute – MEI, 2014.

Hessami M-A, Bowly D R. Economic feasibility and optimisation of an energy storage system for Portland Wind Farm (Victoria, Australia). Applied Energy 2011; 88: 2755–2763.

Hoicka C E, Rowlands I H. Solar and wind resource complementarity: Advancing options for renewable electricity integration in Ontario, Canada. Renewable Energy 2011; 36: 97-107.

Hossain M J, Pota, H R, Mahmud, M A, Ramos, R A. Investigation of the impacts of large-scale wind power penetration on the angle and voltage stability of power systems. IEEE Systems Journal; (2012), 6 (1), art. no. 6026894, pp. 76-84.

Hunt J D, de Freitas M A, Júnior A O. Usinas Hidrelétricas Reversíveis Sazonais no Rio São Francisco: aumentando o armazenamento energético e diminuindo a evaporação. Sustentabilidade em Debate - Brasília, v. 7, n.3, p. 18-33, dez/2016.

IEA - International Energy Agency. Technology Roadmap: Wind energy - 2013 edition. 2013; Paris, France.

IEA - International Energy Agency. Technology Roadmap: Energy storage. OECD/IEA 2014; Paris, France. Available at: https://www.iea.org/publications/freepublications/publication/technology-roadmap-energy-storage-.html Accessed on 16/07/2016.

IRENA. Renewables and Electricity Storage A technology roadmap for REmap 2030 JUNE 2015. Available at: https://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_Electricity_Storage_2015.pdf Accessed on 16/07/2016.

Khatibi M, Jazaeri M. An Analysis for Increasing the Penetration of Renewable Energies by Optimal Sizing of Pumped-Storage Power Plants. IEEE Electrical Power & Energy Conference, 2008.

Libao S, Zheng X, Yixin N, Liangzhong Y, Masoud B. Challenges of large wind generation intermittence and fluctuation for future smart grids. DRPT 2011 - 2011 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 2011.

Luo C L, Far H G, Banakar H, Keung P K, Ooi B T. Estimation of wind penetration as limited by frequency deviation. IEEE Trans. Energy Conversion 2007; 22: 783-791.

Mosadeghy M, Saha T K, Yan R. Increasing wind capacity value in Tasmania using wind and hydro power coordination. Power and Energy Society General Meeting (PES), IEEE, 2013.

Piekutowski M, Halley A, Denholm S. The Future Role of Hydro Plant in Maximising the Integration of Wind Generation The Tasmanian Case Study. Wind Engineering 2012, v 36, n 1, p 19-34.

Rahimi E, Rabiee A, Aghaei J,.Muttaqi K M, Nezhad A E. On the management of wind power intermittency. Renewable and Sustainable Energy Reviews 2013; 28: 643–653.

REN21 - Renewables 2014 Global Status Report, 2014.

Shafiullah GM, Oo Amanullah M T, Jarvis D, Shawkat Ali A B M, Wolfs P. Potential Challenges: Integrating Renewable Energy with the Smart Grid. AUPEC 2010 - 20th Australasian Universities Power Engineering Conference: "Power Quality for the 21st Century". IEEE Computer Society, 2010.

Sinden G. Characteristics of UK wind resource: Long-term patterns and relationship to electricity demand. Energy Policy 2007; 35: 112–127.

Succar S, Greenblatt J B, Williams R H. Comparing coal IGCC with CCS and wind-CAES baseload power options. Fifth Annual Conference on Carbon Capture and Sequestration - DOE/NETL, May 2006

Sundararagavan S, Baker E. Evaluating energy storage technologies for wind power integration. Solar Energy 2012; 86: 2707–2717.

Tamimi A A, Pahwa A, Starrett S, Williams N. Maximizing wind penetration using voltage stability based methods for sizing and locating new wind farms in power system. Power and Energy Society General Meeting, IEEE 2010, Minneapolis, MN, USA, pp. 1-6, July 2010.

Tröster, E., Kuwahata, R., Ackermann, T.: “The Role of Wind Power in the Future European Power System and its Impact on Grid Expansion”; 9th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Québec City, Canada, October 2010.

Vilchez E, Stenzel J. Impact of renewable energy generation technologies on the power quality of the electrical power systems. 22nd International Conference on Electricity Distribution. Institution of Engineering and Technology, 2013.

CONCLUSION AND RECOMMENDATIONS

In the first article of this thesis, the challenges the NE region will encounter to generate renewable energy are examined in detail. One of the biggest difficulties the region will inevitably confront is a projected decline in rainfall, particularly in the São Francisco basin, as a result of climate change. The increased frequency and severity of droughts and the resulting deficit in the São Francisco's streamflow by the end of the century could severely impact hydroelectric and agricultural production in the region. On the other hand, both wind and solar energy potential in the region are predicted to increase as a result of regional climate change. These renewable energy resources will allow for the majority of water flow in the São Francisco River to be devoted to supply urban drinking water, local family farms and irrigation in the semi-arid region. During the coming decades, the cost of water in the Northeast region is likely to escalate. Therefore, it is recommended that the São Francisco River be exploited more for food production and less priority be given to storing water in the Sobradinho reservoir for seasonal hydroelectricity, as large quantities of water in this reservoir are lost to evaporation, particularly when the reservoir is full.

The second article in this thesis estimates the economic viability of renewable and non-renewable energy technologies in the Northeast region of Brazil including their social and environmental externalities. It was concluded that wind energy was the second cheapest energy source in Brazil. While historically large hydroelectric plants were the cheapest source of electricity, the large majority of hydroelectric potential near populated regions of Brazil has already been exploited. This is particularly the case in the NE region of Brazil where wind energy has become the cheapest generation technology. Although the Amazon region still has unexploited hydroelectric potential, plants that have already been built in that region exact high environmental and social impacts, as well as very large transmission costs and energy losses. The Belo Monte hydroelectric plant is now expected to exceed the original budget estimate because several environmental and social obligations have still not been implemented (PONTES, 2017). This may also cause a delay in the planned 2019 completion date. Environmental and social externality costs of fossil fuel plants also have a degree of uncertainty. For example, compared to Europe and the USA, the social health damage costs of pollution from fossil fuel plants in Brazil are likely to be slightly less, because Brazil has a slightly lower population density. On the other hand, GHG damage costs in Brazil could be significantly more than in developed countries, because most regions of Brazil are more susceptible to droughts, floods and temperature increases, and also because agriculture is a major sector of the Brazilian economy.

Since the original 2015 publication of the second article in this thesis, the total investment and construction time of the Angra 3 nuclear plant have more than doubled the initial budget (BORGES, 2017). As a consequence, the LCOE of nuclear power in Brazil has skyrocketed to approximately $140/MWh excluding externalities, making the technology economically unviable. Furthermore, recently the Lapa Solar Park, a 158MW utility scale PV plant was completed with an investment cost of only $175 million (ENEL, 2017). The LCOE including externalities for this PV plant is estimated at under $50/MWh, which means that large scale PV in Brazil is now much cheaper than fossil fuel power and competitive with hydroelectricity and wind energy. The updated LCOE results with a 5% discount rate can be observed in figure A1 of appendix A. Additionally, since the second article was first published, the total installed wind power capacity in Brazil has grown rapidly to more than 11GW and the total onshore wind power potential for the country is now estimated to be around 500GW (SILVA, 2017).

The third and fourth articles examine how variable renewable generation technologies can be integrated into the existing power system. The third article extrapolates existing wind generation data from wind farms already operating in the region and demonstrates the economic and environment advantages of wind energy implementation in the NE region over the use of fossil fuel power. It was found that wind energy generation could potentially substitute all fossil fuel electricity generation and thereby reduce the overall LCOE in the NE subsystem and substantially reduce CO_2 emissions. Since the third article was published the drought in the NE has actually worsened considerably. If the drought continues, then by 2020 hydroelectricity from the São Francisco basin may only be able to generate 15-20% of the NE’s electricity demand. Therefore, in the third and fourth scenarios more biomass and imported hydroelectricity would be required in order to supplement the diminished hydroelectric generation or alternatively fossil fuel generation would be required. Moreover, due to the record low water levels in the São Francisco basin, the flexibility and ability of the NE’s hydroelectric plants to balance the load has been substantially reduced. As a result, most gap filling for balancing net load variations in the NE is presently provided by gas, diesel and oil powered generators. In states such as Rio Grande do Norte these fossil fuel generators frequently have to ramp supply up and down due to stochastic variations in wind generation which can increase maintenance costs. It is recommended that, where possible, these fossil fuel generators be substituted by importing more hydroelectricity from the North region scheduled to balance the net load using load-following controllers. The North region typically has surplus hydroelectricity during the entire wet season (summer and autumn) which can complement diminished wind power generation which typically occurs from January to May. Additionally, analysis should be conducted on the feasibility of reducing the NE's hydroelectric output well below the average minimum generation level only during the early hours of the morning, on days when surplus wind generation is forecast to occur. The overall average hydroelectric minimum generation could still be maintained on a daily basis by compensating with increased hydroelectric generation during peak periods.

Furthermore, energy efficiency measures (such as, utilising variable speed drives) and implementing demand-side-management could also reduce peak demand and thus reduce the need for expensive peak-load following ancillary services. For example, 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.

The fourth article uses the WRF model to simulate wind speeds and wind power considering all wind farms expected to be in operation by 2020. The fourth paper also takes into consideration the minimum generation requirements of the hydroelectric plants in the NE region and therefore more accurately estimates the amount of surplus wind energy that would need to be exported to other regions. It was estimated that by 2020, wind power will generate 57% of the NE load requirements, however approximately 3% of the total generation in the region would need to be exported. Transmission links between the NE and the Southeast subsystems have sufficient capacity for this surplus wind generation to be exported solely to the Southeast region. Results from the optimisation scenarios showed that diurnal wind power from coastal wind farms typically correlates well with the daily load curve, while diurnal wind power from wind farms located inland in the states of Bahia and Piauí was significantly higher at night and before dawn (during low demand periods). Therefore, in order to more easily balance wind generation in the NE subsystem, it is recommended that all surplus wind energy from Bahia and Piauí is exported to the large Southeast/Central-West region. 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.

However, demand-side-management could also 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. 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).

The fifth article reviews the impacts of variable renewable sources on the stability and quality of a power system. It was concluded that there are several existing technologies that can resolve these issues, such as STATCOM, SVC, LVRT and harmonic filters. Modern wind farms have very advanced power electronics that typically incorporate these technologies and therefore, can actually provide some ancillary services including reactive power compensation, voltage regulation and synthetic inertia. Nevertheless, it was found that the integration of wind and solar power into grids with large proportions of coal power generation such as in Victoria Australia is more challenging than grids with flexible hydroelectric generation such as in Brazil. Various energy storage technologies were also examined including the benefits of PHS systems. However, before large investments in new PHS systems are made, it is recommended that cheaper alternatives, such as improved policies that facilitate the integration of variable renewables, are first explored. For example, new market regulations could enable hydroelectric plants to be modified to improve the efficiency and response of their fast frequency control ancillary services. Similarly, if regulated properly, rooftop solar PV combined with advanced battery storage systems, as well as electric vehicle batteries, could provide ancillary services and load shifting to support the grid.

Each power system needs to be analysed individually in order to determine the maximum proportion of surplus wind energy that can be economically utilized by the electricity grid via a range of methods at least cost. Moreover, for each individual power system, the overall cost of wind energy curtailment needs to be weighed against the cost of demand side management, upgrading transmission links to enable exportation and also against the cost of installing PHS or other storage systems. A power system optimised for lowest cost will most likely include a combination of these different methods to manage surplus wind energy. However, without a carbon price or considering environmental externality costs, the lowest cost generation matrix could include substantial fossil fuel power and its associated GHG emissions.

Future research could include a more in depth and detailed analysis of the impacts of climate change on the NE and North regions of Brazil using regional climate model downscaling of the CMIP5 climate and hydrology projections. Integrated water resource management techniques need to be developed in order to address the nexus between climate, water, energy generation and food production. More research needs to be conducted in order to recommend policies that would enable affected regions to manage, and adapt to the consequences of climate change such as prolonged droughts, salinization and desertification. Furthermore, future studies are needed to determine the most effective and sustainable way to replace lost hydroelectric production in the NE and North regions by 2030 and 2050. From the research already conducted in this thesis, it is anticipated that in the NE region, wind energy would make up for the majority of lost hydroelectricity complemented by solar and biomass generation. However, a detailed study still needs to be completed to determine the exact composition of the lowest cost sustainable power system that could supply all 4 Brazilian subsystems in 2030 and 2050 including details on the generation matrix, intraregional and interregional transmission infrastructure, energy importation/ exportation, storage, curtailment, and regulations for demand side management and energy efficiency measures. Such a smart grid requires integrated planning, monitoring and intelligent policies. Brazil already has a largely sustainable low emissions electricity matrix, particularly when compared to the world average and OECD countries. Furthermore, in addition to its hydroelectric resources, Brazil still has abundant unexploited wind, solar and waste biomass resources. As a result, in the coming decade Brazil has the chance to become one of the first major economies to generate 100% of its electricity from renewable and sustainable resources. Therefore, the country has an opportunity to be a world leader in renewable energy integration technologies, policies and planning.

ADDITIONAL REFERENCES

ANEEL – Agência Nacional da Energia Elétrica / Brazilian National Electricity Agency, BIG – Banco de Informações de Geração / Information Bank of Generation; 2017. Available at: http://www2.aneel.gov.br/aplicacoes/ResumoEstadual/ResumoEstadual.cfm accessed on 26/07/2017.

Barnett T P, Pierce D W. When will Lake Mead go dry? Water Resources Research 2008; 44, 3.

Berardy A, Chester M V. Climate change vulnerability in the food, energy, and water nexus: concerns for agricultural production in Arizona and its urban export supply. Environmental Research Letters 2017; 12, 3: 035004.

Borges A. Para concluir Angra 3, governo terá de desembolsar mais R$ 17 bi. Estadão Jornal Digital; 2017. Available at: http://economia.estadao.com.br/noticias/geral,para-concluir-angra-3-governo-tera-de-desembolsar-mais-r-17-bi,70001824398 accessed on 18/07/2017.

Cai W, Borlace S, Lengaigne M, Van Rensch P, Collins M, Vecchi G, Timmermann A, Santoso A, McPhaden M J, Wu L, England M H. Increasing frequency of extreme El Niño events due to greenhouse warming. Nature climate change 2014; 4, 2: 111–116.

de Jong P, Kiperstok A, Torres E A. Economic and environmental analysis of electricity generation technologies in Brazil. Renewable and Sustainable Energy Reviews 2015; 52: 725–739.

de Jong P, Kiperstok A, Sanchez A S, Dargaville R, Torres E A. Integrating large scale wind power into the electricity grid in the Northeast of Brazil. Energy 2016; 100: 401–415.

de Jong P, Dargaville R, Silver J, Utembe S, Kiperstok A. Torres E A. Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid. Applied Energy 2017; 195: 538–555.

Dodds F, Bartram J, editors. The Water, Food, Energy and Climate Nexus: Challenges and an Agenda for Action. Routledge; 2016.

Elliston B, Diesendorf M, Macgill I. Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market. Energy Policy 2012; 45: 606–613.

ENEL. Lapa Solar Park starts operation. Enel Green Power Brasil Participações; 2017. Available at: https://www.enel.com.br/en/media/news/d201706-enel-starts-operation-of-lapa-solar-park-in-brazil.html accessed on 20/06/2017.

Gan T Y, Ito M, Hülsmann S, Qin X, Lu X X, Liong S Y, Rutschman P, Disse M, Koivusalo H. Possible climate change/variability and human impacts, vulnerability of drought-prone regions, water resources and capacity building for Africa. Hydrological Sciences Journal 2016; 61, 7: 1209–1226.

Giupponi C, Gain A K. Integrated spatial assessment of the water, energy and food dimensions of the sustainable development goals. Regional Environmental Change. 2016:1–13.

IRENA. Renewable Energy in the Water, Energy & Food Nexus; 2015. Available at: http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=496 accessed on 18/05/2017.

Jackson T, (2009). Prosperity without growth. Earthscan, London. Available at: http://www.ipu.org/splz-e/unga13/prosperity.pdf accessed on 10/07/2016.

Jenkins K, Warren R. Quantifying the impact of climate change on drought regimes using the Standardised Precipitation Index. Theoretical and Applied Climatology 2015; 120: 41–54.

Mariz C H, Atalla D L. Nordeste, Chesf, Desafios e Oportunidades. Instituto de Desenvolvimento Estratégico do Setor Energético – ILUMINA; 2017. Available at: http://ilumina.org.br/nordeste-chesf-desafios-e-oportunidades-artigo/ accessed on 01/08/2017.

NREL – National Renewable Energy Laboratory. NREL's PVWatts Calculator: Hourly PV Performance Data. NREL; 2016. Available at: http://pvwatts.nrel.gov/index.php accessed on 11/09/2016.

ONS – Operador Nacional do Sistema Elétrico. Históricas da Operação - Geração de Energia; 2017. Available at: http://www.ons.org.br/historico/geracao_energia.aspx Accessed on 16/07/2017.

ONS – Operador Nacional do Sistema Elétrico / Brazilian National Electricity System Operator. RE-3-128-2008 PEL 2009-2010; 2008.

O'Neill D W. The proximity of nations to a socially sustainable steady-state economy. Journal of Cleaner Production 2015; 108: 1213–1231.

Pontes N. Belo Monte paga o preço das polêmicas. Deutsche Welle; 2017. Available at: http://www.dw.com/pt-br/belo-monte-paga-o-pre%C3%A7o-das-pol%C3%AAmicas/a-39023489 accessed on 26/07/2017.

Rockström J, Sachs J D Öhman M C, Schmidt-Traub G. Sustainable Development and Planetary Boundaries, Background Research Paper, Submitted to the High Level Panel on the Post-2015 Development Agenda, Sustainable Development Solution Network, A Global Initiative for the United Nations, 2013.

Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, Schellnhuber H J. A roadmap for rapid decarbonization. Science 2017; 355, 6331: 1269–1271.

Silva F C. Energia Eólica: Panorama atual e futuro no Brasil. ABEEólica - Associação Brasileira de Energia Eólica; 2017. Available at: http://viex-americas.com/2016/wp-content/uploads/2017/07/Francisco-Silva-ABEE%C3%B3lica.pdf accessed on 30/07/2017.

Steffen W, Richardson K, Rockström J, Cornell S, Fetzer I, Bennett E, Biggs R, Carpenter S, Vries W, Wit C, Folke C, Gerten D, Heinke J, Mace G, Persson L, Ramanathan V, Reyers B, Sörlin S. Planetary boundaries: Guiding human development on a changing planet. Science 2015; vol. 347: Issue. 6223, 1259855.

Trenberth K E, Dai A, van der Schrier G, Jones P D, Barichivich J, Briffa K R, Sheffield J. Global warming and changes in drought. Nature Climate Change 2014; 4, 1: 17–22.

World Bank. World Bank national accounts data, and OECD National Accounts data files. The World Bank Group; 2017. Available at: http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG accessed on 30/03/2017.

UNFCCC - United Nations Framework Convention on Climate Change. Global Response to Climate Change Keeps Door Open to 2 Degree C Temperature Limit - New UN Report Synthesizes National Climate Plans from 146 Countries. UNFCCC Press Office; 2015. Available at: http://newsroom.unfccc.int/unfccc-newsroom/indc-synthesis-report-press-release/ accessed on 15/03/2017.

Appendix A

Updated aggregate LCOE results

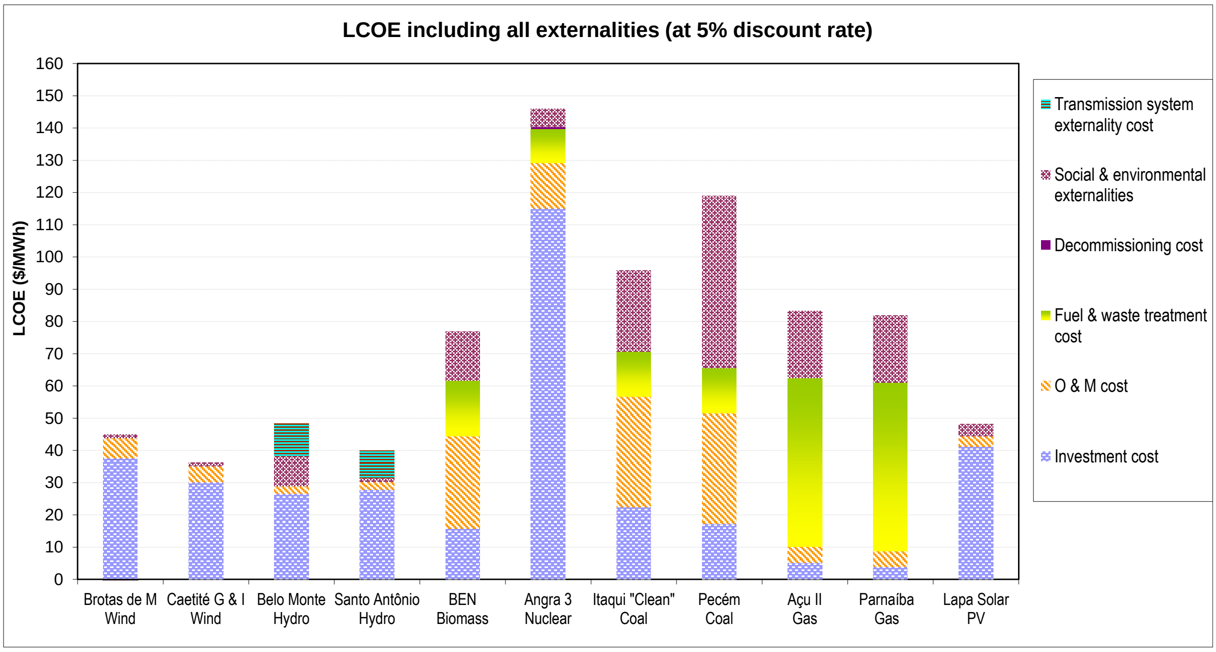

Figure A1: Updated LCOE for nuclear and solar PV plants in Brazil compared to other generation technologies. Results consider a 5% real discount rate with social, environmental and transmission system externality costs.

	Wind Power Capacity by state				**Annual Average Wind Penetration by state**			
	Installed & Operational (MW)	Under Construction (MW)	Planned for Construction (MW)	**Total by 2020** (MW)	Assumed Capacity Factor	**Avg Wind Power** (MWavg)	**2020 Avg Demand** (MWavg)	**Avg Wind Penetration by 2020**
Bahia	1750	1536	2187	5474	50%	2748	3970	69.2%
Ceará	1652	468	483	2603	45%	1182	1641	72.0%
Rio G. d. Norte	3447	573	618	4638	38%	1744	945	184.6%
Alagoas	0	0	0	0		0	779	0.0%
Paraíba	63	95	0	157	42%	67	771	8.6%
Pernambuco	703	81	82	866	40%	349	2186	16.0%
Piauí	1102	464	195	1761	43%	757	599	126.3%
Sergipe	35	0	0	35	42%	15	588	2.5%
NE Total	**8752**	**3215**	**3566**	**15534**	**44%**	**6861**	**11479**	**59.8%**

Figure A2: Updated wind power capacity and electricity demand data in the Brazilian NE subsystem by 2020 (Sources: ANEEL, 2017; ONS, 2017 and ONS, 2008) and corresponding gross wind power penetration. Note that growth in electricity demand may be reduced by energy efficiency measures and new tariffs. On the other hand, long-term demand may increase as a result of economic development and climate change.

Appendix B

The complementarity of wind, PV and CST power in Bahia

In chapter 3, the maximum penetration of wind power in the state of Bahia was determined. In this appendix the integration of wind energy with the addition of solar PV and concentrated solar thermal (CST) power is investigated. The maximum wind power penetration in chapter 3 was estimated to be 47%, however, wind power in Bahia is typically greater at night than during daylight hours. Therefore, the impact of adding solar PV will be investigated and the maximum feasible proportion estimated. Solar radiation data (NREL, 2016) for Bom Jesus da Lapa (which is a semi-arid municipality in Bahia) was used to estimate the hourly, daily and monthly electricity production from solar technologies. Average hourly plane of array Solar Radiation statistics (in W/m^2) are used to estimate the annual and diurnal solar PV electricity generation. Therefore the viable penetration limit of variable renewable resources (wind and PV) without storage can be determined. Above this limit the feasibility of adding a proportion of CST power with energy storage is investigated. Average hourly Direct Normal Solar Radiation statistics (in W/m^2) are used to estimate the annual and diurnal CST power. It is assumed that the CST plants will have at least 8 hours of storage per day available for use (in one block) at any chosen time of the day or night, similar to the approach taken by Elliston et al (2012). Using an iterative approach, the maximum annual combined penetration of wind, PV and CST is calculated considering the hourly electricity demand profile of Bahia.

Results with wind and solar penetration

In figure B1 the average hourly statistics for plane of array and direct normal solar radiation are shown for the month of August in Bom Jesus da Lapa, a municipality of Bahia which is most likely to see more solar power development given that solar radiation in this region is the highest in the country. The August plane of array and direct normal solar radiation curves were normalised as a percentage of their maximum values.

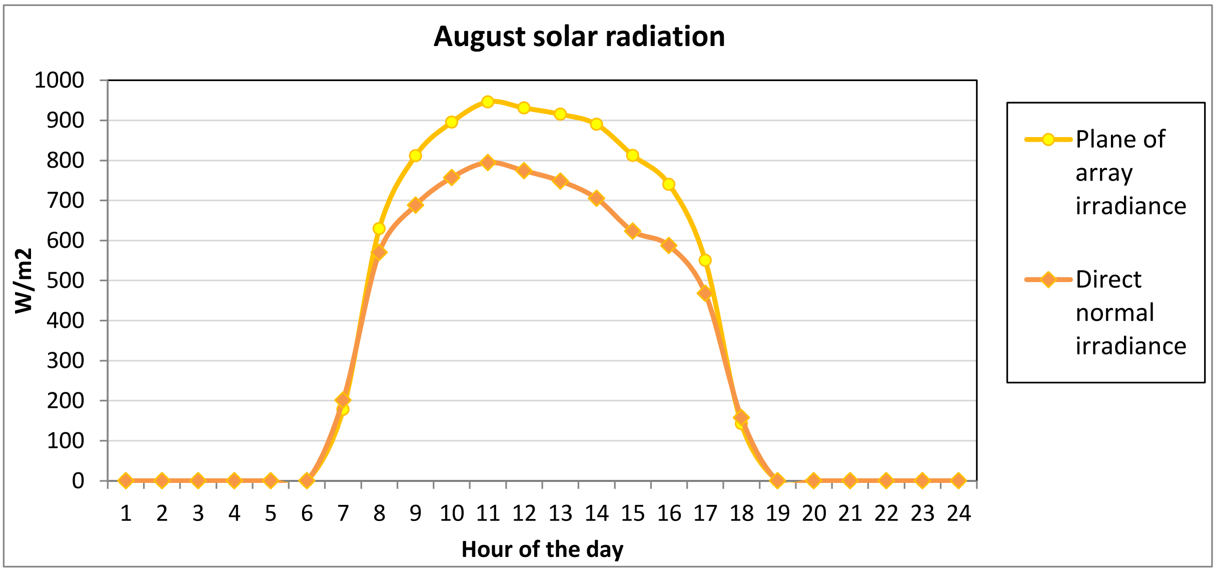

Figure B1: Average hourly plane of array solar radiation and direct normal solar radiation in Bom Jesus da Lapa, Bahia for August. Source: (NREL, 2016).

To obtain the maximum penetration of variable renewables and avoid significant curtailed energy, wind penetration remained at 47% and this allowed for up to 12.5% solar penetration. Therefore it can be concluded that the maximum possible penetration of variable renewable energy resources (wind and PV) without energy storage in Bahia is almost 60%.

The addition of CST power with storage to optimize the renewable mixture

CST power with thermal energy storage allows solar energy to be delivered to the grid in a more dynamic way. That is, by delaying the dispatch of CST generation by approximately 8 hours so that the peak in CST generation coincides with the peak in net load (electricity load minus variable renewables), which occurs around 19:00h, a 70% penetration of renewables (wind, PV and CST) can be achieved. In this case the optimum annual penetrations of wind, PV and CST would be 47%, 12.5% and 10.2%, respectively, and only 1% of this renewable energy would need to be exported to other states. To achieve these high penetrations would require accurate weather forecasting and sufficient transmission expansion in order to minimise spilled energy. Given the above average wind power in the month of August, the penetrations (specifically for the month of August) of wind, PV and CST would be 64%, 14% and 12%, respectively, however, 2.3% of this generation would need to be exported to other states. Therefore, during the month of August only 12.3% of demand would need to be supplied by hydroelectricity. This configuration of renewable energy generation is illustrated in figure B2.

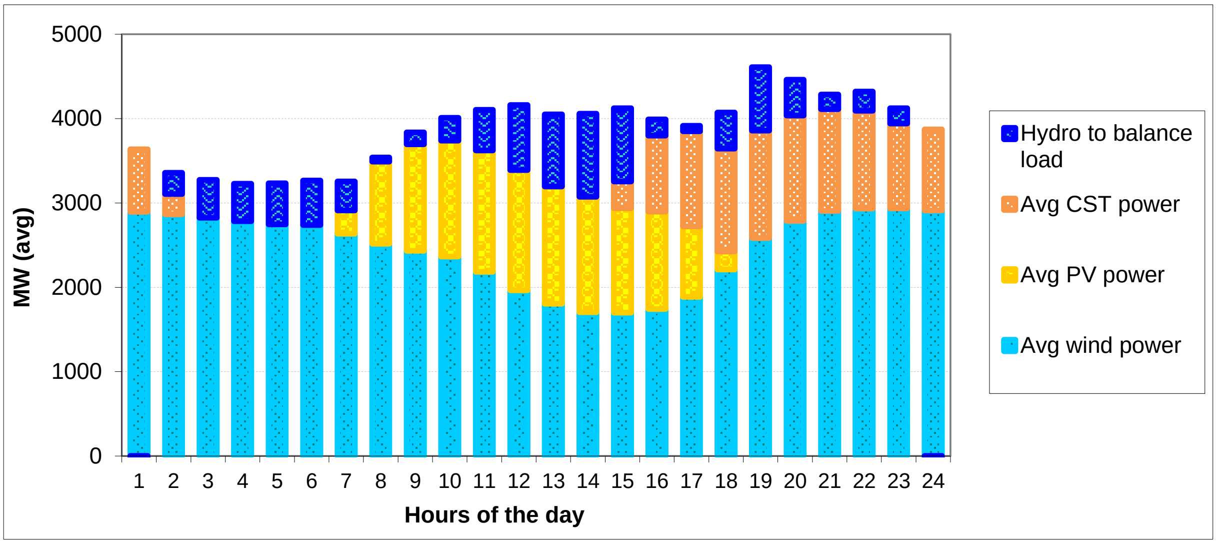

Figure B2: Diurnal contribution from wind, PV, CST power and hydroelectricity to the hourly load curve in Bahia during the month of August.