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Economic, technical and environmental analysis of renewable and non-renewable electricity generation technologies in Brazil

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ABSTRACT

This study compares the economic viability of five renewable energy technologies – wind, solar photovoltaic, concentrated solar thermal, biomass and wave power – to various other technologies including hydroelectricity, nuclear power, coal power and gas power sources. The Levelised cost of Electricity (LCOE) is calculated for 13 different case study projects in Brazil and compared to the LCOE in Australia and other countries abroad. The economic impact of carbon taxes in Brazil and from the sale of carbon credits is also investigated. 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 impact of carbon credits and taxes on the LCOE of the various case studies was then examined. Only at a carbon price above \$125/tCO_{2eq} does electricity produced by coal power without carbon collection and sequestration (CCS), become more expensive than large scale solar technology in Brazil. 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. The final part of this study analyses the ability of solar and wind power to supply electricity to the grid during peak demand periods in the Northeast of Brazil. A comparative analysis was performed between the electricity load curve for a typical year and a typical day, and statistical data for wind speed and solar irradiation. The results show that correlations exist and renewable energy can help support regional temporal demand in the existing electricity grid in an efficient and more environmentally sustainable manner than electricity generation from fossil fuels. A complementarity was also found between hydroelectricity (the region's main energy resource) and wind and solar energy. That is, in the months of the dry season (when the cost of energy is more expensive and the hydroelectric availability is low) there is a greater availability of wind and solar energy. Therefore it will be shown that more investment in these two renewable sources would help to diversify the Northeast's electricity supply matrix, securing it against the effects of droughts.

Keywords: Renewable Energy; Solar; Wind Power; Wave Power; Hydroelectricity.

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RESUMO

Este estudo compara a viabilidade econômica de cinco tecnologias de energias renováveis- eólica, fotovoltaica solar, térmica solar concentrada, biomassa e energia das ondas - à várias outras tecnologias, incluindo hidrelétrica, nuclear e fontes de carvão e gás. O Custo Nivelado de Energia, sigla em inglês (LCOE) é calculado em 13 projetos de estudo de caso diferentes no Brasil e comparado com o LCOE da Austrália e de outros países no exterior. Também será investigado o impacto econômico das taxas e da venda de créditos de carbono no Brasil. Os resultados iniciais mostraram que usando uma taxa de desconto baixa de 5%, as hidrelétricas tiveram o menor LCOE, mas foram somente um pouco mais baratas em relação aos estudos de caso em energia eólica. No entanto, utilizando uma taxa de desconto alta de 10%, um dos estudos de caso em energia eólica teve, na verdade, o menor LCOE. Energia solar fotovoltaica (PV) foi considerada a tecnologia mais cara, seguida pela energia das ondas e a energia térmica solar concentrada (CSP). Assim, será mostrado que PV e CSP conectados a rede distribuída são pouco desenvolvidos no Brasil devido ao alto preço associado com a importação de equipamentos de energia solar para o Brasil e também, devido à política do governo federal. O impacto das taxas e créditos de carbono sobre o LCOE de vários estudos de caso foi então examinado. Apenas a um preço de carbono acima de \$125/tCO_2eq a eletricidade produzida por energia à carvão sem coleta e sequestro de carbono (CCS), torna-se mais cara do que a tecnologia solar em larga escala no Brasil. Os custos ambientais e sociais externos de usinas de combustíveis fósseis e de grandes represas hidrelétricas (na região amazônica) também são discutidos nesse trabalho. Será demonstrado que a energia eólica torna-se a tecnologia de geração mais barata no Brasil, uma vez que todos os custos das externalidades e transmissão são levados em consideração. A última parte deste estudo analisa a eficácia da energia eólica e da energia solar no fornecimento de eletricidade à rede, durante os períodos de pico no Nordeste do Brasil. Uma análise comparativa foi realizada entre a curva de carga elétrica em um ano e dia típicos, e dados estatísticos da velocidade do vento e da radiação solar. Os resultados mostram que existem correlações e que energia renovável pode ajudar, apoiando a demanda regional em certos períodos na rede elétrica existente, de uma maneira eficiente e mais sustentável ambientalmente do que a geração elétrica de combustíveis fósseis. Uma complementaridade foi também encontrada entre a hidroeletricidade (principal fonte de energia da região) e as energias eólica e solar, ou seja, nos meses da estação seca (quando o custo da energia é mais caro e a disponibilidade hidroeletrica é baixa), há uma maior disponibilidade de energia eólica e solar. Portanto será exposto que mais investimentos nessas duas fontes de energia renováveis ajudariam diversificar a matriz de fornecimento elétrico do Nordeste, protegendo-a dos efeitos das secas.

Palavras-chave: Energia Renovável; Solar; Eólica; Energia das Ondas; Hidroeletricidade.

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LIST OF ABREVIATIONS, ACRINIMS AND SYMBOLS

AEP	American Electric Power
ANEEL	Agência Nacional da Energia Elétrica/Brazilian Electricity Regulatory Agency
ASC	Advanced Super Critical
ATSE	Australian Academy of Technological Sciences and Engineering
BEN	Bioenergia
BIG	Banco de Informações de Geração/Generation Information Bank
BREE	Bureau of Resources and Energy Economics
CAES	Compressed Air Energy Storage
CCC-ISOL	Isolated Fossil Fuel Consumption Account
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Collection and Sequestration
CDM	Clean Development Mechanism
CERs	Certified Emission Reductions credits
CO_2	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equivalent
COE	Cost of Energy
COELBA	Companhia Elétrica da Bahia/Electric Company of Bahia
CSP	Concentrated Solar Power
CST	Concentrated Solar Thermal
EPE	Empresa Pesquisa Energética/Energy Research Company
EPRI	Electric Power Research Institute
ESAA	Energy Supply Association of Australia
EUAs	European Union carbon Allowances
FC	Fuel Cell
FIES	Incentive Fund for Solar Energy
GHG	Greenhouse Gases
HOMER	Hybrid Optimization Model for Electric Renewables
IEA	International Energy Agency
IBGE	Instituto Brasileiro de Geografia e Estatística
IGCC	Integrated Gasification Combined Cycle
INPE	Instituto Nacional de Pesquisas Espaciais/National Institute for Space Research
IMF	International Monetary Fund
IPI	Taxes on Industrialized Products
IPCC	Intergovernmental Panel on Climate Change

IRR	Internal Rate of Return
kWh	Kilowatt hours
Wp	Kilowatt peak
l	litres
LCA	Life Cycle Analysis
LCOE	Levelised Cost of Electricity
Wp	Watt peak
MJ	Mega joules
MME	Ministério de Minas e Energia/Ministry of Mining and Energy (Brazil)
MW	Megawatts
MWe	Megawatts (electrical)
MWh	Megawatt hours
MRET	Mandatory Renewable Energy Target
MRS	Metropolitan Region of Salvador
NE	Northeast
NEA	Nuclear Energy Agency
NEEDS	New Energy Externalities Development for Sustainability
NEM	Australian National Electricity Market
NO_x	Nitrogen Oxides
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
O & M	Operations and Maintenance
ONS	Operador Nacional do Sistema Elétrico/Electrical System National Operator
PF coal	Pulverised Fuel black coal
PV	Photovoltaic
PWR	Pressurised Water Reactor
REC	Renewable Energy Credits
RET	Renewable Energy Target
SEPLANDE	Secretaria de Estado do Planejamento e do Desenvolvimento Econômico
SO_2	Sulphate Dioxide
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation
STCs	Small-scale Technology Certificates
SWERA	Solar and Wind Resource Assessment
UNFCCC	United Nations Framework Convention on Climate Change
WCMG	waste coal mine gas

1. INTRODUCTION

1.1. Renewable energy growth and viability

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 countries with large tropical and subtropical areas such as Brazil and Australia where around 80% of the population live near the coast, 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. Therefore this study aims to identify the reasons and barriers that prevent a rapid shift to these renewable technologies.

For more than 10 years wind power has been developing at a commercial level in Europe and yet in Brazil it only makes up a small fraction of electricity generation. 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 (PEREIRA et al, 2012). But more recently in Brazil, due to increasing fossil fuel prices, the local manufacture of wind turbines and the introduction of carbon credits through the Clean Development Mechanism, large scale wind farm projects are now viable and have been undertaken by private enterprise (BITENCOURT et al, 2012 and DE JONG et al, 2013). These projects will contribute significant amounts of electricity to the national distribution grid.

Both Brazil and Australia have areas with high percentages of sunlight per year and this free and clean resource can be used to generate solar power. In Australia there are already many public and private buildings which have solar panels connected to the electricity distribution grid. The viability of distributed grid connect photovoltaic (PV) solar systems is continually improving and has reached grid parity in Australia (APVA, 2012). However due to the high costs of solar power equipment in Brazil and the lack of government incentives, there are very few grid connected utility scale solar power projects installed in Brazil (BITENCOURT et al, 2012). These large scale solar power projects are not yet commercially viable without financial assistance, but semi-arid areas in the interior of Brazil and Australia would benefit from such technology.

Wave and tidal power generation prototype technology has existed for more than a decade, but thus far has not achieved a large scale commercial level of production. Brazil and Australia have enormous wave power potential given that most large population centres are located on or near the ocean. Given the density of water, power and regularity of the oceans and the tides, large scale wave and tidal power generation have the potential to be cheaper than wind power and are less susceptible to intermittencies compared to wind power and solar PV (RICARTE and ESTEFEN, 2003).

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, environmental and technical 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 several different case study plants following the NEA-IEA-OECD (2010) methodology. The environmental and social costs of each case study plant are also estimated following the ATSE (2009) methodology. Finally the technical ability of solar and wind power resources to support electricity demand in the Northeast of Brazil is analysed.

The remainder of section 1 discusses the justification of this study. In section 2 of this study the specific objectives are detailed. Section 3, examines the Brazilian energy sector focussing on the Northeast region and also examines the Brazilian wind and solar power potential. In section 4, government policy in Brazil is compared to that in Australia and carbon capture and storage technology is examined. Several articles and publications on the viability of renewable energy technologies are reviewed in section 5. Section 6, outlines the methods used for the economic, environmental and technical analysis of various electricity generation technologies. In section 7 and 8 the case studies and the principle data sources for this thesis are outlined. The results of the economic analysis of the case studies are explained in section 9 and a sensitivity analysis is conducted in section 10. In section 11 the cost of generating electricity in Brazil is compared to that in Australia. In section 12 the environmental and social impacts of the different generating technologies are analysed and the costs of extended transmission systems are estimated. In section 13 the technical ability of renewable energy sources to efficiently supply the electricity demand in the Northeast of Brazil is detailed. The principle findings and conclusions of this study are discussed in section 14.

1.2. Environmental justification

Ultimately, anthropogenic environmental damage on the planet, if allowed to continue unaddressed, will have increasingly harmful consequences for humanity. The more critical environmental issues that already require action to reduce their impacts on our ecosystem include the depletion of the ozone layer, the deterioration of the nitrogen cycle (nitrate pollution and eutrophication), air pollution, acid rain, pollution of fresh water systems and the oceans, loss of biodiversity and global warming (ROCKSTRÖM et al, 2009). It is unlikely that global warming can be averted. Temperatures have already risen as a result of human activities since the industrial revolution and will continue to rise until governments, industry and corporations do something to address the issue. Our daily activities, science and engineering can influence how fast global temperatures will rise over the next century and thus influence the collateral effects of global warming.

The earth will not end even if the average temperature rises 4 to 5°C by the end of this century, however sea levels will rise, weather patterns will become more erratic and extreme, rainfall patterns will be affected, some productive land and existing food production areas will suffer desertification and other areas may become more productive. These changes will negatively affect the food supply and living conditions certain populations and in some cases require whole communities to migrate to more habitable areas. Other population centres may be less affected. Poorer communities that rely on subsistence agriculture and nations that cannot afford to rapidly adapt, particularly those in low-lying tropical and subtropical areas, will likely suffer the most (BROCKMAN, 2006). If nothing is done to prevent these humanitarian disasters from occurring, the resulting consequences could be conflict over agricultural, water and energy resources.

But things can be done to reduce the amount of greenhouse gases (GHG) emitted into the atmosphere and thus the rate temperatures rise can be slowed. This at least, would allow communities and the environment to adapt more gradually to the impacts of global warming and significantly reduce the cost to humanity. Slowing climate change by reducing GHG emissions (and preventing other environmental problems) are moral humanitarian issues that will require action.

A sustainable and industrial ecological approach would be to reduce and change the way we use and produce energy. Reducing energy consumption through energy efficient technology will reduce impacts of energy consumption and is also logical economically and in terms of resource consumption, but overall world energy consumption is still likely to grow as the third world and developing countries (such as India, China and Brazil) grow their economies and become more industrialized. Therefore to reduce GHG emissions and other environment impacts, we will also need to change the way we produce energy. That is, energy we produce, including that for transport, needs to be non-polluting, sustainable and economically viable. Therefore this study aims to examine the viability of various renewable energy technologies.

1.3. Economic justification

Besides the environment grounds to switch from fossil fuels to renewable energy sources there are also economic reasons. This justification is a simple case of diminishing supply and increasing demand. Fossil fuel prices are predicted to rise as oil resources, in particular, diminish and this is likely to have a negative effect on the world economy. As world oil consumption increases and the available resources of cheap crude diminish, it is likely that the price of oil will significantly increase over the next 50 to 100 years (PEREIRA et al, 2012). This increase will possibly also cause an increase in other fossil fuel prices such as gas and coal, as demand for those resources will grow. The 2008 spike in oil prices also saw a spike in coal and gas prices (IMF, 2013). Currently the world economy is highly dependent on oil and other fossil fuels for the transportation and energy production sectors. In turn most other industries are, at least indirectly, partly dependent on these two sectors. In 2008 the world economy suffered a massive slowdown which was partly triggered by a spike in oil prices. Therefore apart from the environmental problems, if humanity does not switch to alternatives to fossil fuel and its dependence on oil, the world economy will likely suffer severe downturns in the coming decades as depleting oil reserves will mean higher extraction costs (PEREIRA et al, 2012). On the positive side it is expected that the economic viability of renewable energy technologies (wind, solar, wave and geothermal power) will continue to significantly improve in comparison (DELUCCHI & JACOBSON, 2011). Nevertheless renewable energy technologies are often still falsely perceived as expensive, unreliable and incapable of supplying sufficient power (DALTON et al, 2009).

2. OBJECTIVE

In this section the objectives of this study are explained. The principle objective of this study is to analyse the economic, environmental and technical viability of renewable energy technologies compared to traditional electricity generation technologies in Brazil. It is anticipate that the results of this study will assist energy planners to make more objective and informed decisions regarding new electricity generation projects.

2.1. Economic viability of renewable energy technologies

The first part of this study compares the Brazilian energy sector to Australia and the rest of the world, and also focussing on the future energy supply challenges faced by the Northeast (NE) region of Brazil. In particular, wind and solar energy potential and the growth of these technologies in Brazil are analysed as well as government policies supporting the development of these resources.

The primary aim of this study is to compare the Levelised Cost of Electricity (LCOE) of different electricity generation technologies by using various power plant projects in Brazil as case studies. Given the particular energy generation challenges faced by the NE region (see section 3.1), the majority of the case studies chosen are within the NE.

The case studies include the Brotas Macaúbas wind farm Project, Caetité, Guanambi and Igaporã wind farm complex, Belo Monte hydroelectric plant, Santo Antônio (run of river) hydroelectric plant, Angra III nuclear power plant, Pecém Energy coal fired power station, Itaqui "Clean" coal power station, Parnaíba gas fired power station, Açu II gas fired power station, Tauá solar PV energy system, Pituaçu Solar PV system, Bioenergia (BEN) biomass plant and a hypothetical CSP plant at Bom Jesus da Lapa.

All 13 case studies are analysed in order to assess their economic viability and are also compared with some examples of electricity generation plants in Australia. For those applicable projects the possible contribution of incentives from the sale of carbon credits is examined in order to assess the effect this has on their viability.

Additionally the effect on the LCOE by increasing carbon taxes from zero to $300 per tonne of CO_2 will be examined for those projects which could be subject to future carbon taxes.[1] (Case studies which could be subject to future carbon taxes include Pecém Energy coal fired power station, Itaqui "Clean" coal power station, Parnaíba gas power station, Açu II gas power station, and also the Belo Monte hydroelectric dam).

2.2. Evaluate the environmental and other impacts of electricity generation case studies

Besides examining the LCOE, this work aims to examine the environmental and social impacts of traditional generation technologies in Brazil by analysing those case study projects that cause significant amounts of 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. In this sense it is intended that the advantages and disadvantages of small scale distributed renewable energy systems can be compared to very large scale centralised power plants.

2.3. Evaluate the correlation of renewable energy with electricity demand load curves

This study aims to show the advantage of increasing the proportion of grid connected solar and wind power in the Northeast of Brazil by studying the correlation between the monthly variation of the load curve in a typical year and some characteristic parameters taken as representatives of renewable energy availability. The principle objective is to demonstrate that wind and solar power can support temporal demand variations in the electricity grid load curves (during a typical day and year) in a reasonably efficient manner.

Likewise, by studying the reverse correlation between the monthly availability of water in the São Francisco reservoirs and the availability of wind and solar power during a typical year, the benefits of solar and wind power to the Northeast's electricity supply matrix can be realized.

[1] In this study all monetary values are expressed in US dollars ($) unless otherwise specified.

3. THE BRAZILIAN ENERGY SECTOR

This section reviews some of the main statistics in the Brazilian electricity generation sector and also some of the electricity generation difficulties faced by the Northeast region of Brazil. The growth of wind and solar energy in Brazil and the national potential of these resources are examined.

The electricity supply matrix for Brazil consists of 64.5% hydroelectricity, about 6.2% imported power which is mostly hydroelectricity, 7.9% biomass and 1.6% wind power (see figure 1). Therefore more than 80% of electricity generation is from renewable energy sources (ANEEL – BIG, 2013). However the 1.6% (or 2000MW) of installed wind power capacity only generates approximately 0.7% of electricity (ONS, 2013) due to the technologies low capacity factor.

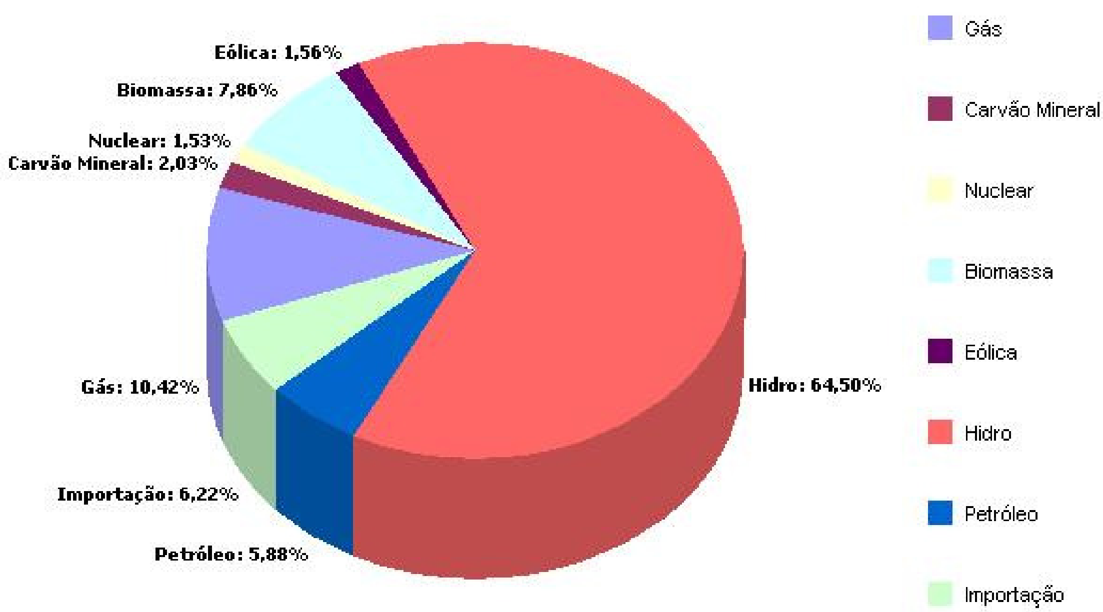


Figure 1: Brazilian Electricity Matrix has a total installed capacity of 131,500 MW. Source: ANEEL (2013).

Brazil compares very well to the rest of the world where on average renewable energy sources account for only 19.5% of electricity generation (MME, 2012). By comparison, in Australia renewable sources contribute 10.1% to electricity generation which includes 2.3% from wind power (BREE, 2012).

As a result of Brazil's large hydroelectric resources and significant use of ethanol fuel and biodiesel, 44.1% of the Brazilian primary energy matrix comes from renewable sources, which again compares very well to the global average of only 13.3% (MME, 2012). In Australia renewables contribute only 4.3% to the total primary energy supply (BREE, 2012). However as of 2011, only 0.5% of Brazil's national electricity supply was generated from solar or wind resources (MME, 2012). Today wind power generates approximately 0.7% of Brazil's electrical energy (ONS, 2013).

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. However large hydroelectric projects in these regions will have high environmental and transmission line costs, and relatively low energy density (MARTINS and PEREIRA, 2011).

3.1. The Northeast region

The Northeast (NE) region represents almost one-fifth of Brazil's geographic area and is the homeland of 53.6 million people, as well as being the driest part of the country. While Brazil overall has the world's largest water resources, this particular region is mostly semi-arid and suffers from frequent droughts, which can also affect the power supply, as the majority of the electricity matrix is supplied by hydroelectricity. The region is privileged with huge solar and wind resources, while at the same time it imports a significant percentage of electricity from the North and Southeast regions (ONS, 2011a) as shown in figure 2.

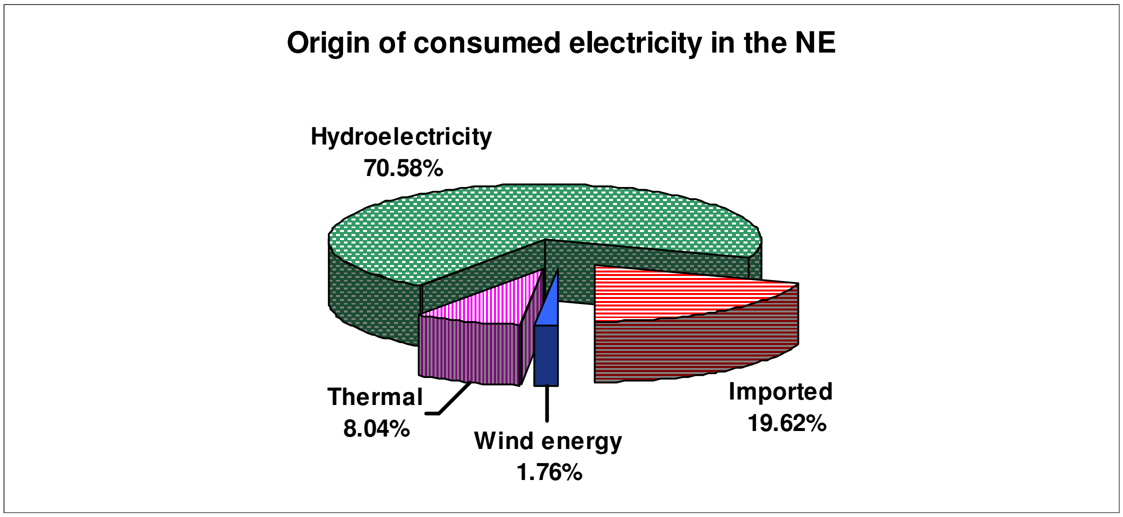


Figure 2: Origin of electricity consumed in the NE region for 2011. (Currently in the NE, "Thermal" electricity generation is from fossil fuels and biomass. "Imported" consists mostly of hydro from other regions). Source: ONS (2013).

The main river of the NE region is the São Francisco River, which is responsible for 65% of the region's power supply (ONS, 2011b). With already five dams and several hydroelectric plants along its course, it is no longer possible to build big hydroelectric facilities as was done in the past. Additionally, there is a controversial project by the Brazilian government, already under construction, which aims to divert part of the river's water flow in order to irrigate remote semi-arid territories. The project may prove to be ineffective in the long term due to reduced rainfall in the São Francisco basin as a result of climate change and is also criticised due to its high investment. Additionally the completion of this project may further deteriorate the actual situation of hydroelectricity stagnation, resulting in a reduction of electricity production in the context of constantly rising electricity demand. 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 the lengthy transmission lines. Additionally, large hydroelectric dams, such as Belo Monte, planned for the Amazon basin region have limited power output during the dry season and cause significant environmental conflicts.

The hydroelectric potential near populated areas is almost entirely saturated in most of the country. This is particularly true for the Northeast (NE) region which is the driest region in the country receiving only a small percentage of the annual total national rainfall. The semi-arid region of the NE suffers from severe droughts, most recently in 2012. Due to Brazil's reliance on hydroelectricity, the drought of 2001 caused massive power shortages in the NE region and also nationally. However regional changes in long term temperature and rainfall patterns for the NE region due to Global Warming may threaten hydroelectricity production to an even greater degree. Over the next 60 years temperatures in the interior of the NE are predicted to increase approximately 4 to 5°C and rainfall will decline approximately 25 to 50% in semi-arid areas and up to 80% in coastal regions. This will cause a reduction of up to 60-90% in water flow rates for various rivers in the NE by 2070 (TANAJURA et al 2009). The impacts of climate change will not be restricted to the NE and will most likely also threaten the hydroelectricity production in other regions of Brazil. For example according to Pereira de Lucena et al (2010) the climate in the North region, which today is very humid, will become drier toward the end of the century resulting in less rainfall.

The higher temperatures and decline in rainfall predicted for the NE, as a result of climate change, will also cause a significant increase in the regions average solar radiation levels. During the same period the wind power potential in Brazil and particularly in the North and Northeast regions is also predicted to increase considerably. Using the same IPCC climate models as Tanajura et al (2009), Pereira de Lucena et al (2010) estimate that by 2070, wind power generation potential will more than double the 2001 reference baseline potential and by 2100 it will more than triple the baseline data.

Forecasts for coming years, for Brazil, indicate an increase of more than 4% in the Gross Domestic Product per year. Growth in Brazil's electricity consumption is directly proportional to the growth in the economy and according to the National Energy Plan - PNE 2030 (MME, 2007), "In 25 years, the total [annual] consumption of electricity in Brazil will be close to 1,200TWh, which indicates an average growth of 4% per year from 2005." At the end of 2005, the country's installed capacity was just over 90,000 MW. In 2030, the country's installed capacity is predicted to exceed 220,000 MW.

The growth in energy consumption in the NE is expected to be in line with the national figure. However as shown in figure 2, the NE region is already deficient in energy production and in 2011, almost 20% of its electricity consumption was imported from the North and Southeast regions of Brazil. In 2010, 24% of the NE's electricity was imported (ONS, 2013). Therefore during the coming decades the NE region in particular, will be faced with particular challenges in order to maintain electricity generation with the growing demands in consumption. There are several fossil fuel power stations being planned and others already under construction (MME, 2011b). The contribution of electricity generated from fossil fuels has already increased from 8% in 2011 to 14% in 2012 and as a result the percentage of imported electricity decreased (ONS, 2013). Additionally the debate continues over the possible construction of nuclear power plants in the Northeast, supported by the existence of uranium deposits in the region and a desire to further develop the national nuclear industry. The "Plano Nacional de Energia - PNE 2030"/Brazilian National Energy Program 2030 (MME, 2007) which reflects the government strategy for expansion of the Brazilian electricity generation infrastructure, forecasts the need for an additional 4000 megawatts from nuclear power by 2025 (yet this will only contribute 2% to the country's installed capacity). This will mean the construction of two nuclear power plants in the Northeast and two more in the Southeast. According to this plan, the Brazilian Generation Matrix will see at least a 10% increase in the proportion of thermal electricity generation (including nuclear power) by 2030. A more sustainable and cleaner alternative could be to invest more in renewable energy generation given that the NE region is privileged with excellent solar and wind resources.

Whatever solution is adopted for electricity generation in the coming years, there is undoubtedly a need for planning, because the period of execution for large projects, such as a nuclear power plant or a big hydroelectric plant is in the order of 5 to 10 years. At the present moment Brazil is located at an interesting point in terms of energy planning, and current wind and solar technologies could play an important role in the near future. In this context, wind power development is accelerating in the Northeast. In particularly the states of Bahia, Ceará and Rio Grande do Norte; have experienced a rapid growth in wind farm deployment due to their favourable conditions in terms of wind speed, frequency, distribution and turbulence.

3.2. Brazilian Wind and Solar energy potential

Brazil's National Electric Energy Agency (ANEEL) held the country's first ever wind-only energy auction on December 14, 2009. Around 1,800 megawatts (MW) were contracted with energy from 71 wind power plants scheduled to be delivered by July 1, 2012. The auctions in 2010, on August 25th and 26th produced more intense competition and wind energy contracts were awarded totalling more than 2047.8 MW. The average price for wind energy was $64.78 per MWh, a 12% reduction from December 2009. In the last auctions held in 2011 of the 429 wind farm projects with a total capacity of 11,000MW registered (EPE, 2011b), only 44 wind farm projects totalling 1068MW were actually contracted and wind tariffs dropped to an average of $49.30 per MWh which make them lower than tariffs for biomass, small hydro and natural gas power plants (EPE, 2011a). However, given that this latest price for wind power in Brazil is the lowest prices in the world, there is some doubt as to whether some of these contracted wind farms will actually be built according to schedule if at all (NIELSEN & SCIAUDONE, 2012). In figure 3, the expected growth from 2010 until 2020 in installed capacity of various generation technologies is shown (large hydroelectricity has been omitted). It can be observed that the rate of expected growth of wind power capacity is greater than all the other energy sources being exploited in Brazil (with the exception of large hydro). However, it should be noted that wind turbines operate with a capacity factor of only about half that of the thermal electricity generation technologies.

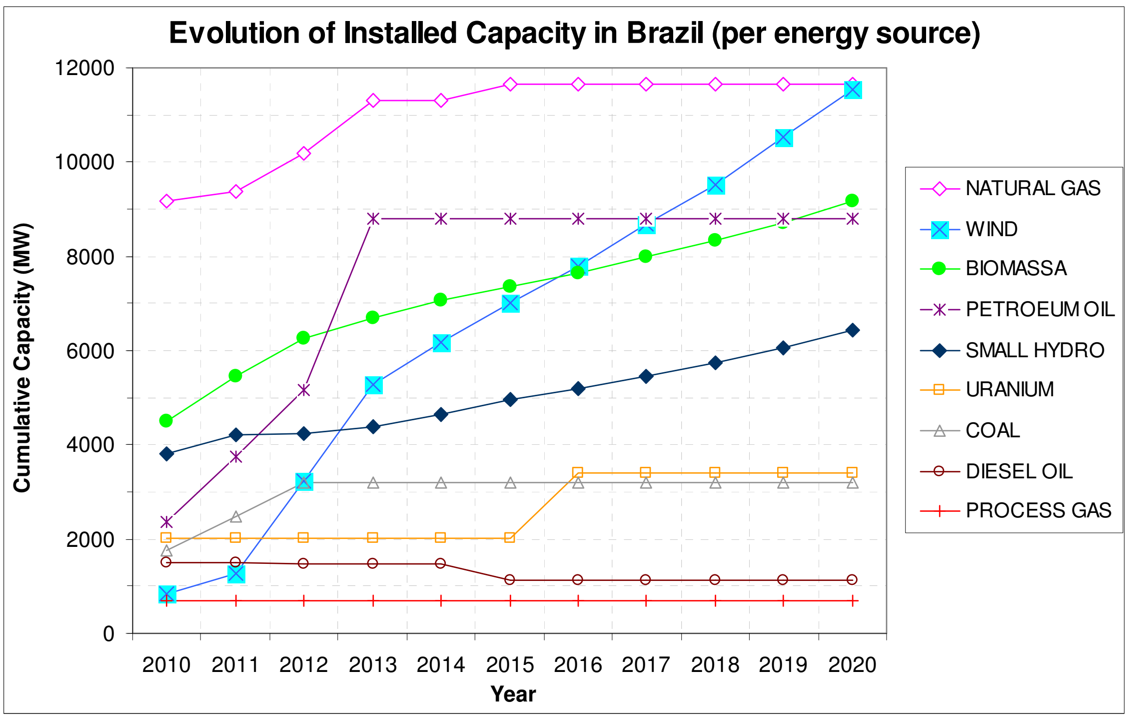


Figure 3: Forecast growth of various generation technologies in Brazil until 2020. Source: MME (2011b).

As a result of the auctions held by ANEEL from 2009 to 2011, in Bahia alone, 57 wind farms with a capacity of 1418MW are contracted to be installed in the next few years, and recently the state licensed locations for an additional 133 wind farms with a total capacity of 3,200 MW (SECOM, 2012). The NE region's power potential, the best in the country, has also attracted the attention and business of international manufacturers of wind turbines and blades (in 2011 both ALSTOM and Gamesa opened wind turbine factories in the Metropolitan Region of Salvador, Bahia).

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 (Amarante et al, 2001) shown in figure 4. Today wind turbines are typically installed at heights of 80-100m and at these heights the wind power potential and capacity factors are significantly greater. Therefore if 100% of Brazil's wind power potential was installed during the next 20 years, this would satisfy the National Energy Plan's predicted increase in energy consumption until 2030, even taking into consideration an average capacity factor of only 35% for wind power.

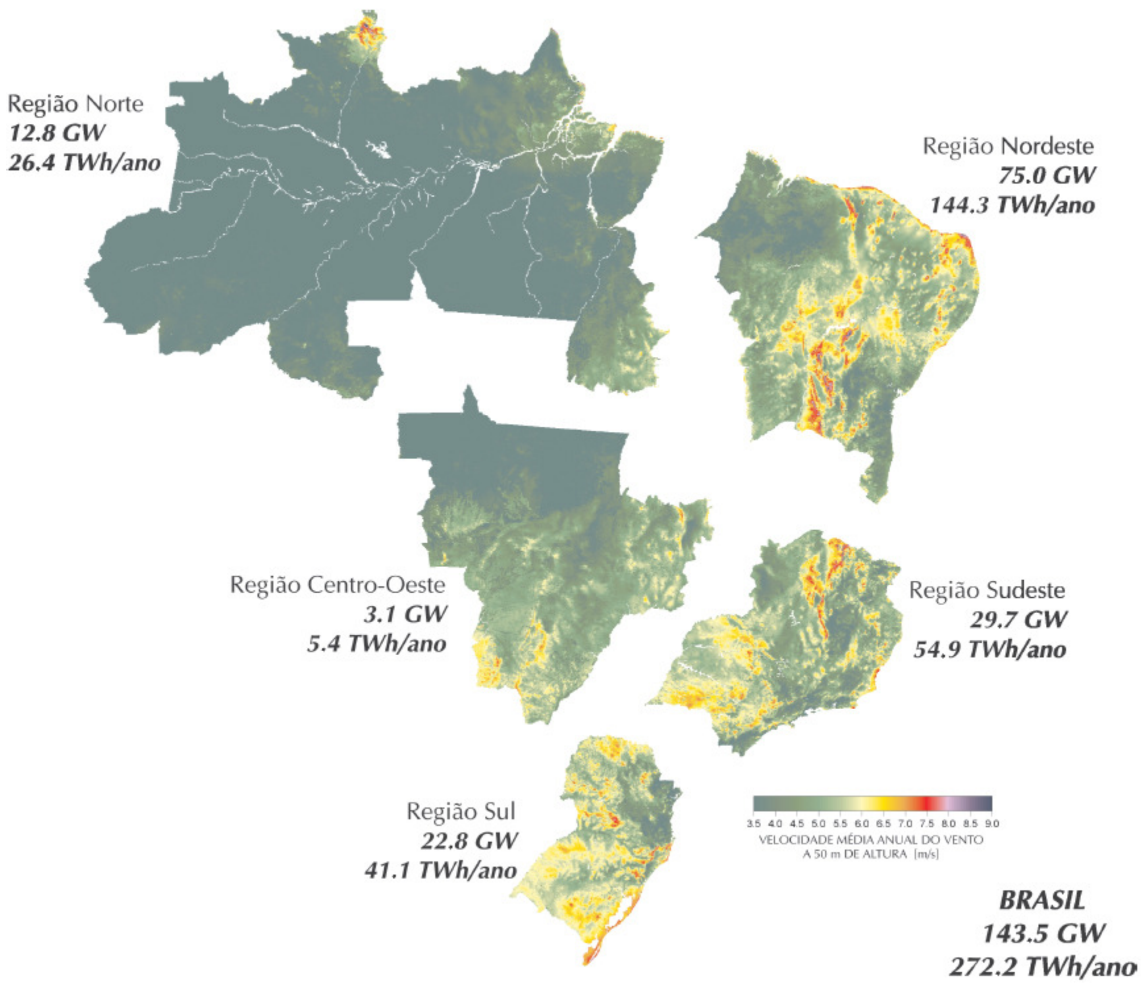


Figure 4: Brazilian atlas of wind power potential divided by region. Source: Amarante et al, (2001).

Several wind energy assessments and atlases have been completed for Brazil. However the development and penetration of the solar technology in Brazil is lagging far behind. But this is not because there is a lack of solar potential. Solar irradiation in most regions of Brazil is excellent as can be seen in figure 5.

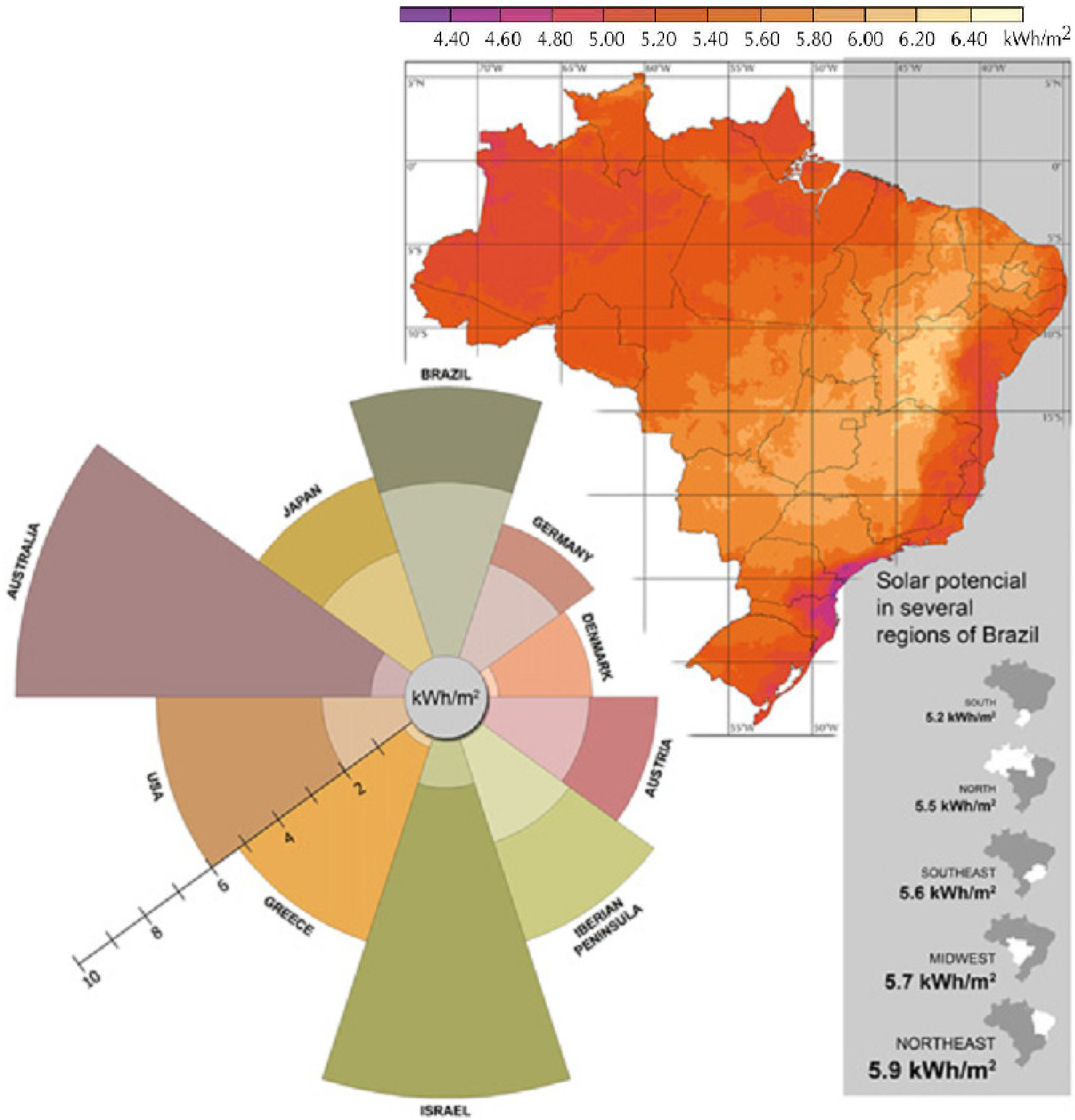


Figure 5: Left: Comparison of seasonal solar variability. Right: Annual average daily solar radiation in Brazil (kWh/m^2 on an inclined plane). Source: Martins and Pereira (2011).

In figure 5, Martins and Pereira (2011) demonstrate that solar energy resources in Brazil compare well to other countries where the solar energy market is more advanced. 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.[2] Additionally the seasonal and inter-annual solar variability are low in Brazil compared to other countries, because most of

[2] 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 (NREL, 2011). Therefore the average daily energy output from a Solar PV system in the NE would be about 700-750kWh/m^2.

the country's territory is located in tropical regions. Therefore applications such as hybrid PV – diesel plants in the arid areas of the Northeast and in the Amazon could provide cost affective electricity for remote villages. The potential in the Amazon is huge as the region is not connected to the grid and relies on expensive diesel generators.

Additionally grid-connected PV systems in commercial and urban areas could match well the high daytime air-conditioning loads. But despite the great potential for solar resources the installed PV capacity in Brazil is tiny and until very recently was mostly restricted to universities and research institutes. Compared to PV, solar hot-water heating technology is used significantly in Brazil. Currently, more than 5 million m^2 of solar heating collectors are installed with a payback period of 3-4 years (MARTINS and PEREIRA, 2011), but this technology could be exploited a great deal more.

Most dwellings in Brazil still have electric hot-water showerheads which are inefficient and contribute to the evening peaks in electricity demand (see section 13.6). If these devices were compulsorily phased out and replaced with solar hot-water installations, or in the cases where this was not possible, with gas or electric hot-water tanks (which are more efficient and can operate at off-peak times), then the evening peaks in electricity demand would be considerably reduced (NETO, 2008). This type of energy efficiency scheme requires legislation and significant government incentives to be effective, but would reduce overall electricity consumption and the pressing need to expand the Brazilian electricity generation matrix.

All solar PV panels installed in Brazil need to be imported, as currently there are no local manufacturers and therefore these imported solar panels are subject to high importation taxes. In Brazil, the turnkey price in 2011 for Tauá Solar, a utility scale grid connected PV system was $5/Wp (BITENCOURT and DE JONG et al, 2012). In Australia the minimum turnkey price for a grid connected utility scale PV system in 2011 was $2.50/Wp. Figure 6 shows the PV module price in Australia from 1993 to 2011.

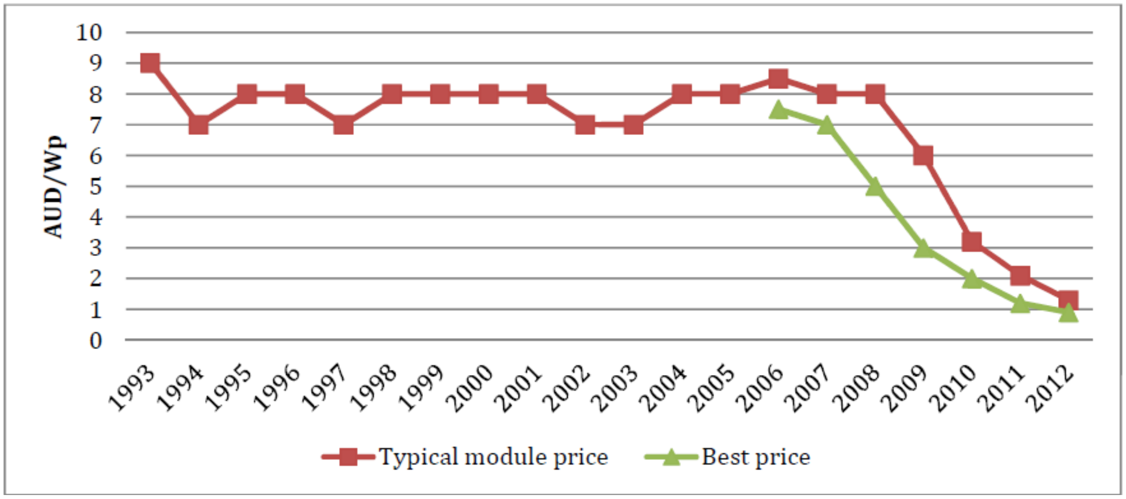


Figure 6: Australian PV module prices 1993-2011 in Australian dollars (Au$1.00 = US$1.00 as of May 2013). Source: APVA (2012).

The 2011 average price for solar panel modules in Australia was $2.10/Wp, but by the end of 2011 was as low as $1.20 (APVA, 2012). This is a fraction of the price of PV modules in Brazil which retail for approximately $5.94 per watt peak (GRANDIN, 2011) and on a utility scale cost approximately $3.22/Wp (COELBA - Grupo Neoenergia, 2012).

Additionally solar and wind power are still at a disadvantage from other government barriers such as subsidies for fossil fuels consumption in remote areas like the Amazon as well as the lack of reliable information on the variability of intermittent solar and wind energy resources. Consultations with stakeholders revealed that the main issues are a lack of government regulation and fiscal policies, such as tax incentives and defined pricing for intermittent sources such as wind and solar power (MARTINS and PEREIRA, 2011).

4. GOVERNMENT POLICY AND CARBON CAPTURE AND STORAGE

This section evaluates some government policies in Brazil aimed at developing renewable energy technologies. Similarly, Australian government policies on renewable energy are also examined. Additionally, the effectiveness of the carbon market (taxes and credits) and the viability of carbon capture and storage are also discussed.

4.1. Government Policy in Brazil

Rüther and Zilles (2011) argue the case for grid-connected PV generation in Brazil and the establishment of a feed-in-tariff. The costs of hydroelectricity in Brazil are expected to increase due to environmental restrictions and the large transmission line distances to the remaining potential sites. Transmission and distribution infrastructure and power loss are considerable in a country as large as Brazil, therefore there is an added value (beyond the cost per kilowatt-hour) for distributed PV systems. Grid connected PV could offer a number of advantages in Brazil including, the distributed nature of urban-scale PV and high solar radiation resource availability which is complementary to seasonal hydroelectric availability. Additionally commercial regions with high midday air-conditioning loads have a demand curve which correlates well with solar irradiation, particularly in the summer months when daytime peak loads are at their annual maximum. Therefore Rüther and Zilles (2011) argue for the establishment of a feed-in-tariff program for PV systems in Brazil, as cost-effectiveness alone, has not been enough to establish a strong local PV market and widespread adoption of this technology.

Until very recently there was a lack of 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, ANEEL approved a resolution that allows consumer micro and mini installations of renewable sources (including PV) to be connected to the grid. The rules *"reduce barriers to installing small distributed generation, including micro-generation up to 100 KW of installed power, and mini-generation from 100 kW to 1 MW. [Similar to a feed-in-tariff] the standard creates the Energy Clearing System, which allows consumers to install small generators at the consumer location and exchange energy [for credits] with the local distributor. The rule applies to generators that use promoted* *energy sources (hydro, solar, biomass, wind and qualified cogeneration systems)"* (ANEEL, 2012).

With the exception of the above resolution, currently there are no effective government incentive programs that directly support marketing, promotion and development of the solar energy industry. The only government policies that (albeit indirectly) support solar heating systems to improve the energy efficiency in buildings are PROCEL and also ‘‘Minha Casa, Minha Vida’’ which requires the use of solar hot-water heaters in low income financed dwellings (MARTINS and PEREIRA, 2011).

There are a number of proposed government programs and policies presently under discussion in the Brazilian Congress. For example PL 3623/2012 will provide for exemption from Taxes on Industrialized Products (IPI) levied on commercializing the domestic market of solar panels and equipment whose purpose is the generation of solar energy. PL 3422/2012 will provide for exemption from the Tax on Industrialized Products (IPI) levied on commercializing the domestic market of equipment, blades and towers whose purpose is the generation of wind energy. PL 2562/2012 will provide for tax incentives for using solar energy in homes and businesses. Until 2020, taxpayers will be able to deduct the income tax portion of the costs incurred for the acquisition of goods and services required for the use of solar energy. PL 630/2003 will provide incentive funding for research and promote the production of electrical and thermal energy from solar and wind energy, and other renewable sources (PARLAMENTO BRASILEIRO, 2013). This last proposed law has been under discussion and negotiated since 2003, therefore, as with all the above proposals, it is very difficult to predict when or if these policies will be approved in the near future.

To date the federal government has not adopted subsidies such as feed-in tariff for renewable energy sources, where the government pays the difference between the cost of the plant and the sale price of energy, though this is practiced in many European countries. However a similar subsidy system is being adopted by the government of Ceará, which created the Incentive Fund for Solar Energy (FIES). The first plant to benefit from this scheme is the MPX Tauá solar project, (STATE GOVERNMENT OF CEARÁ, 2011).

Carbon taxes and credits are a possible alternative to help improve the viability of these renewable projects. Currently, carbon credits are undervalued, but in the future it is anticipated that carbon markets will enable the construction of more renewable energy power plants. In the long term, according to Nicholson et al (2012) the carbon price in Australia is expected to rise to above US$75 per tonne of CO_{2eq} by 2030 and exceed US$150 per tonne of CO_{2eq} by 2050. However recent trends suggest these predicted carbon prices may not come to fruition (see section 4.2 and figure 7).

Regulated under the Kyoto Protocol, the Clean Development Mechanism (CDM) enables the trading of carbon credits and allows developed countries to invest in projects to reduce GHG emissions in developing countries. This is a practical example of an international regulation that is aimed at minimizing the effects of climate change and promoting clean energy technology on a large scale.

4.2. Government Policy in Australia

So how does government policy in Brazil compare to that in Australia? With the exception of Luxembourg, Australia is the largest emitter of greenhouse gases per capita amongst OECD countries (IEA, 2011). In December 2007 the Australian government ratified the Kyoto Protocol and committed Australia to meeting a GHG abatement target of 8% above 1990 levels until 2012. In 2009 the government extended the Mandatory Renewable Energy Target Scheme (MRETS) by increasing the target for 2020 from 9500 million kWh to 45,000 million kWh Valentine (2010). This target, if achieved, would ensure that 20% of Australia's electricity supply comes from renewable energy sources by 2020. However Kuwahata et al (2010) argue that *"Australia is faced with a great challenge to break away from the traditional sources of energy for power generation and increase the share of renewable-based power generation from 8% to 20% in 10 years."*

Additionally, Valentine (2010) outlines a number of failings in the new Renewable Energy Target (RET) policy. First the government agreed to allow waste coal mine gas (WCMG) to be included in the RET scheme as an "eligible energy source" even though it is not a renewable energy source. WCMG, also known as coal seam gas, is becoming a booming industry, but it is not a clean technology. Besides CO_2 emissions, there are a number of other environmental issues including concerns that the cumulative effects from the chemical extraction process and fracking could impact on Australian ground water in the Great Artesian Basin (READFEARN, 2011).

According to Valentine (2010) the concession allows the coal mining industry to apply to obtain renewable energy credits (REC) for electricity generated from WCMG-fired power plants. In essence this concession is a subsidy to the coal mining industry and effectively widens the cost gap between renewable such as wind power and coal fired power stations.

Currently 68.2% of Australia electricity is generated by coal, (partly due to the heavy subsidies the industry receives) and 19.4% by gas (BREE, 2012). Similar to the US, the coal industry in Australia, has powerful lobby groups that inhibit a shift to renewable technologies as these clean technologies would negatively affect the powerful coal industry.

The coal industry also benefits from two government programs: COAL21 which is a $1 billion public and private subsidy over 10 year for research into reducing emissions from coal power stations and the CCS Flagship program which is a $2.4 billion grant over 9 years for carbon capture and sequestration research. (Note, Au$1.00 = US$1.00 as of May 2013). In comparison the Clean Energy Initiative (the main renewable energy support program) provides only $465 million across numerous renewable energy technologies (VALENTINE 2010). Despite the huge financial benefits that the coal sector receives, there are no operating power plants with a fully-integrated CCS system on an industrial scale in Australia or anywhere in the world (see section 4.3).

Valentine (2010) also criticises the limited duration of the RET program where no additional RET growth has been allowed for beyond 2020 target of 45,000 million kWh per year even though the program expires in 2030. Thus in lieu of a proper carbon tax or emissions trading scheme the RET does not allow for sustained growth in the renewable technology sector.

In Australia a carbon tax of $23 per tonne of CO_{2eq} was implemented on the 1st July, 2012. However, as a result of an agreement made between the Australian government and the European Commission on the 28th August 2012 this carbon tax will become ineffective. From mid-2015 Australia's biggest carbon polluters will be able to use European Union carbon Allowances (EUAs) or the UN-backed Certified Emission Reductions credits (CERs) to meet a portion of their carbon liabilities. In 2012 EUAs and CERs were trading around €6.90 ($8.50) per tonne of CO_2 and €0.60 ($0.74) per tonne of CO_2 respectively. The Australian government also scrapped the proposed $15/tonne of CO_2 floor price for permits. As a result

Australia's top polluters will save at least \$2.5 billion, between 2015 and 2020, compared to the initially proposed floor-price scenario (REUTERS 2012). The Australian government agreed to fully link the carbon trading scheme with the European system by 2018, however without the implementation of the CO_2 floor-price, the carbon trading scheme could become ineffective.

The reality is that over the last 5 years, since a peak in the carbon price of €29/tonne of CO_2 in mid-2008, the EUA (and CER) price have tended to have several price crashes (see figure 7) rendering the trading schemes as completely ineffective at reducing emissions.

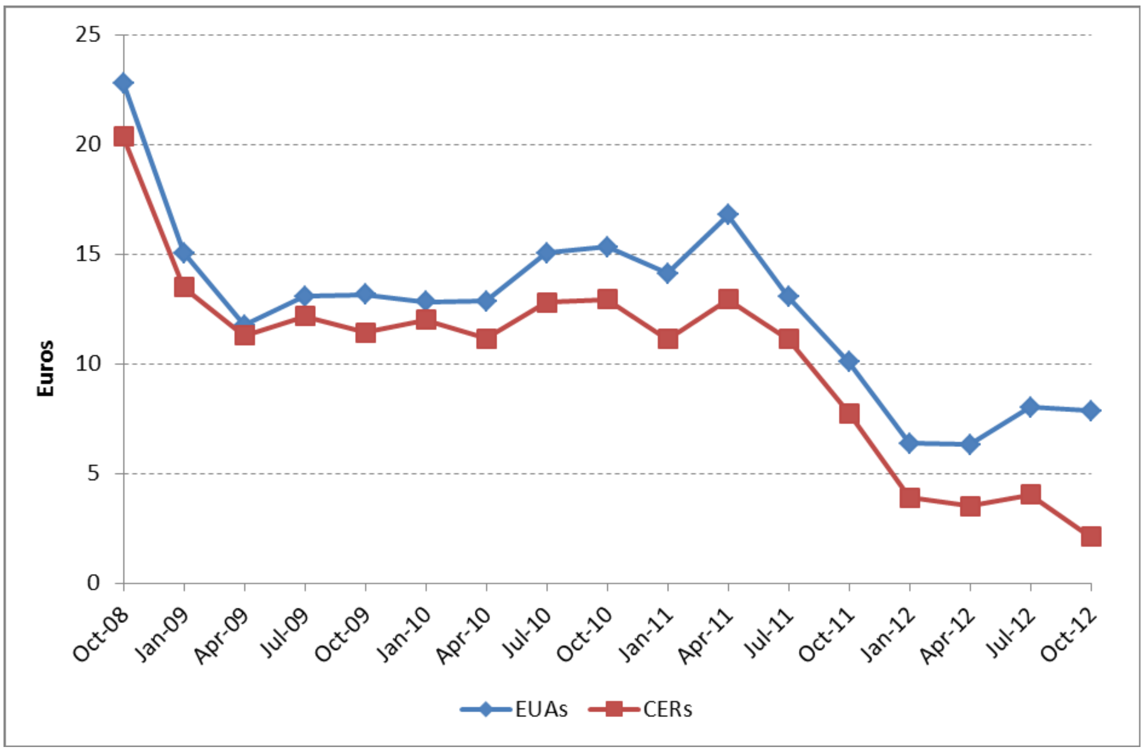


Figure 7: The price in Euros (€) of EUAs and CERs since October, 2008. Source: Point Carbon EUA OTC assessment (2012) apud Parliament of Australia (2012).

In 2010 the Chicago Climate Exchange ceased trading operations after the carbon credit price fell to \$0.05/tCO_2. In April 2013, EUAs and CERs fell to lows of €3/tCO_2 (\$3.90/tCO_2) and €0.25/tCO_2 (\$0.32/tCO_2) respectively (POINT CARBON, 2013). According to the IEA (2010) a carbon price of between \$150-300/tCO_2 is needed to effectively reduce world CO_2 emissions and enable large scale transition to CCS, wind, biomass, PV, CSP and ocean power technologies. The IEA (2010) BLUE Map scenario, where 2005 emission levels are halved by 2050, would require a carbon price of \$175/tCO_2. (The BLUE Map scenario would enable the stabilisation of CO_2 levels at 450ppm). The reality is that at current levels however, carbon taxes or trading schemes are *"like rearrange the deck chairs on the Titanic"* and world CO_2 emissions continue to increase between 2-3% per year. Rather than an ineffective "green-washing" fiscal policy implemented by vote sensitive politicians, what is needed to greatly reduce CO_2 emissions is a solution that uses innovative technology implemented by engineers and scientists and this needs to be supported by both rigid government legislation and corporate policy.

4.3. Carbon Capture and Storage

In an effort to slow and prevent further global warming, much scientific and media attention is currently focused on reducing CO_2 emissions. There has been a lot of research on Carbon (CO_2) collection and sequestration (CCS) including publications by the Global CCS Institute (2012), the IPCC (2005), Nicholson et al (2012) and Succar et al (2006). Other more radical ideas to reduce the impact of global warming involve geo-engineering, which could include such schemes as cloud production via aerosol injection (MORIARTY & HONNERY, 2012 and BROCKMAN, 2006), increasing the amount of sea algae to absorb CO_2, burying of organic waste deep in the ocean (BROCKMAN, 2006), to name a few. However, these schemes including CCS, are very much end of the line (end the pipe) solutions. They address the effects of GHG emissions rather than the cause and do not really address other environmental problems nor have they not been implemented on a commercial or large scale.

In late 2009 American Electric Power (AEP) began operating the first and only fully-integrated carbon dioxide (CO_2) capture and storage (CCS) project at an existing coal-burning power plant (Mountaineer) in New Haven, West Virginia. However, due to the continued weak economy, AEP made the business decision to place the project on hold and in May 2011 it discontinued operation (AEP, 2011). There are many other examples around the world of CCS projects being delayed, put on hold or scrapped and as mentioned earlier there is not a single example of a coal or gas fired power station with fully integrated CCS on an industrial scale anywhere in the world. When it comes to projects implementing CCS for coal fired power stations this is not surprising, as according to the IPCC (2005) electricity from coal power with fully integrated CCS is approximately double the cost of electricity from conventional coal power stations (currently about $60/MWh in the USA). This is partly because the CCS process would increase the fuel requirement of a coal fired power plant by at least 25% (IPCC, 2005).

However it should be mentioned that pre-combustion CCS applications are proving to be effective and viable in certain industries with point sources of CO_2 emissions, such as natural gas processing, synthetic fuel plants, hydrogen production and fertilizer production plants. According to the Global CCS Institute (2012) there are currently 8 examples of large-scale integrated pre-combustion CCS projects in operation. 6 of these plants capture and store CO_2 from natural gas processing plants. 5 of these 8 plants are in North America and store CO_2 by injecting it into mature oil fields which enables enhanced oil recovery.

5. VIABILITY OF RENEWABLE ENERGY LITERATURE SURVEY

In this section several authoritative reports and published scientific articles on electricity generation are reviewed. Scientific articles and reports included in this survey examine the LCOE of renewable and traditional energy technologies as well as their environmental impacts. Additionally, various scientific articles on the variability and complementarity of renewable energy resources are also reviewed.

5.1. International studies on the cost of generating electricity

Besides the above NEA IEA OECD (2010) analysis comparing the LCOE for the principle generation technologies in Brazil, there have been almost no studies focussing on the cost of generating electricity in Brazil. Various international studies comparing the LCOE have been completed which do include renewable technologies such as wind solar and wave power. Figures 8 and 9, taken from the NEA IEA OECD (2010) study shows the regional ranges of LCOE for nuclear, coal, gas and onshore wind power plants with a 5% and 10% discount rate.

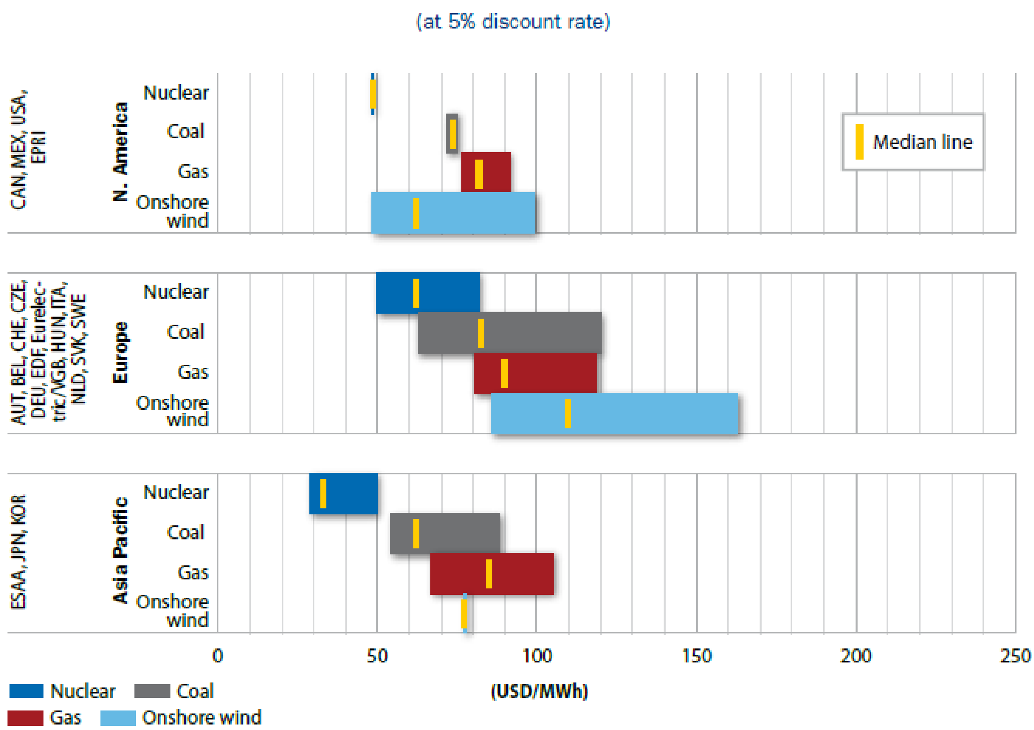


Figure 8: Regional LCOE at 5% discount rate. Source: NEA IEA OECD (2010).

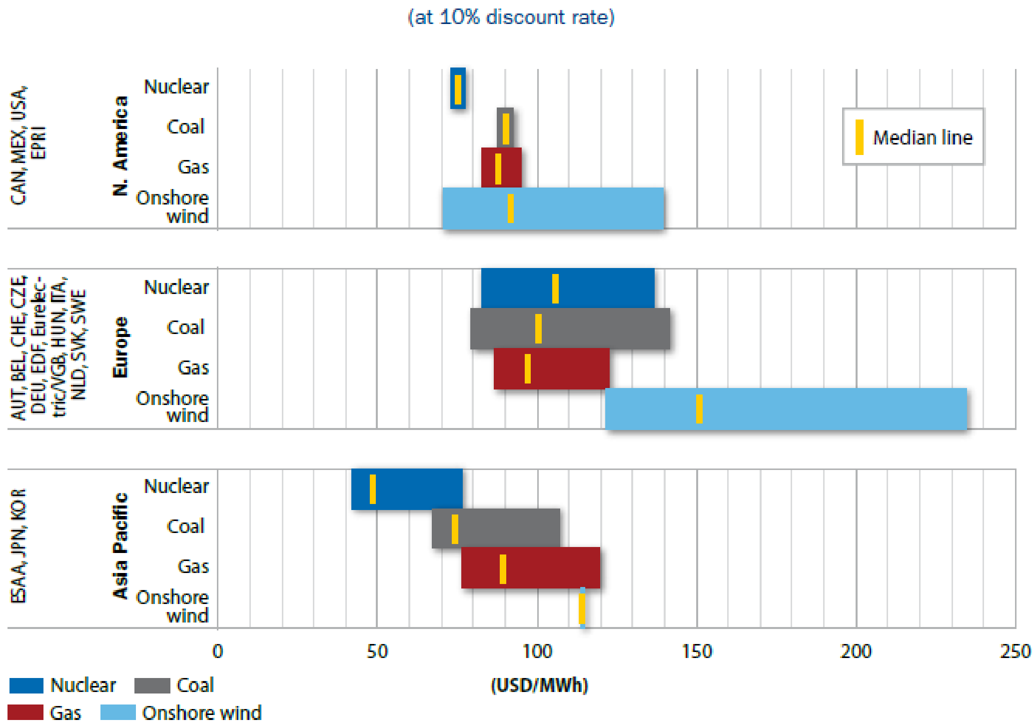
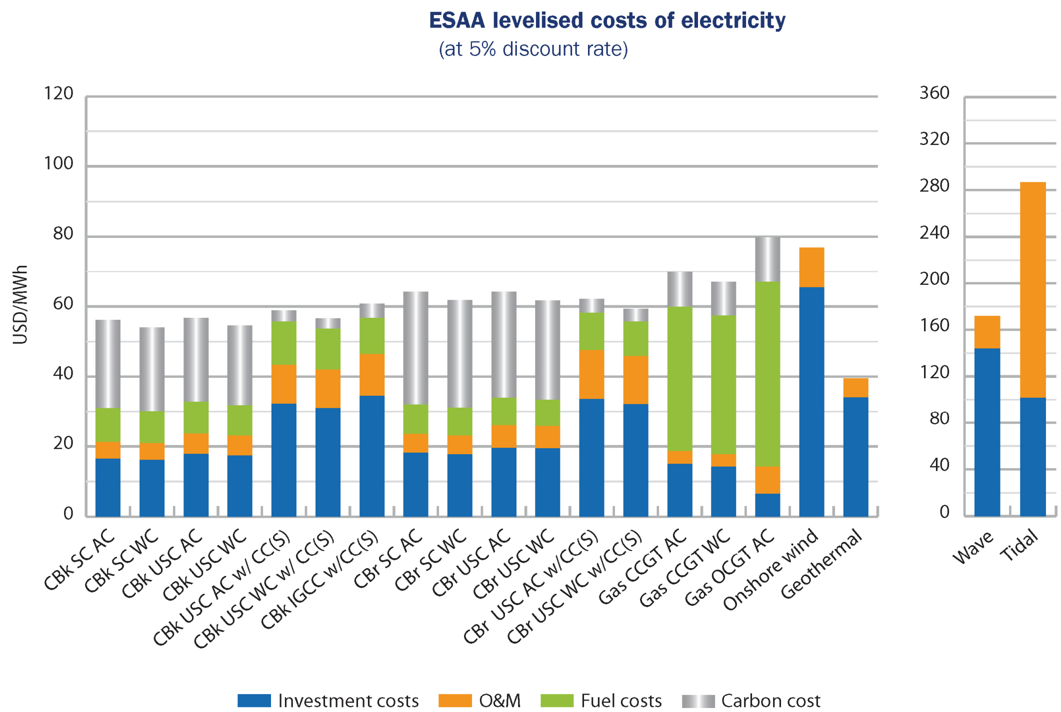


Figure 9: Regional LCOE at 10% discount rate. Source: NEA IEA OECD (2010).

However wind power is the only renewable technology shown in the comparison. The NEA IEA OECD (2010) study has a good comparison of LCOE in Australia which includes wind, geothermal, wave and tidal energy generation technologies. Figure 10 shows the LCOE for the Energy Supply Association of Australia (ESAA). The NEA IEA OECD (2010) report also has LCOE data comparing traditional generation technologies in Brazil and the results can be seen in figure 11.



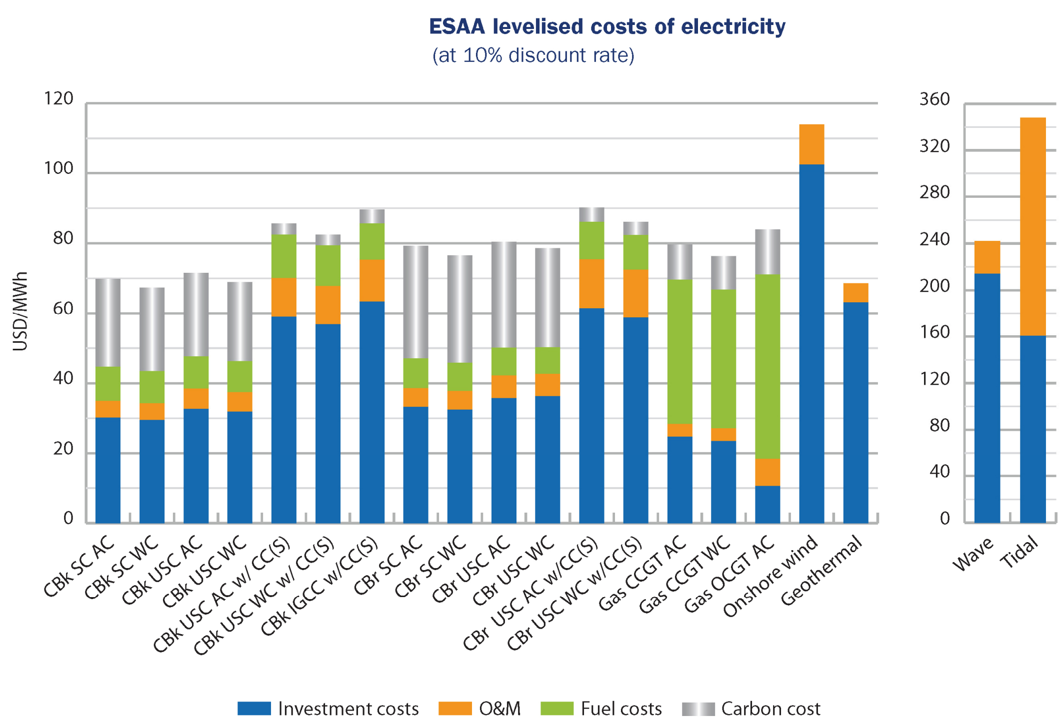
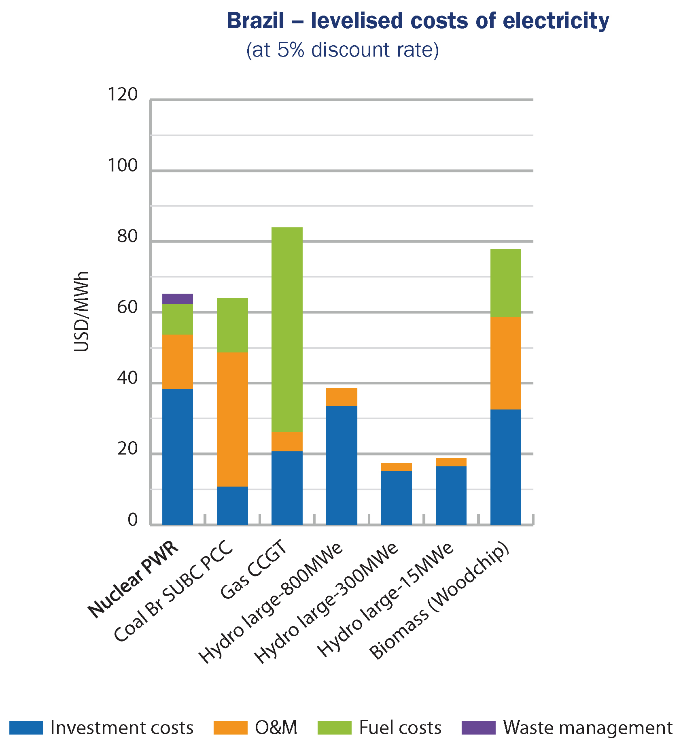


Figure 10: LCOE in Australia. Key: AC Air-cooled; CCGT Combined cycle gas turbine; CC(S) Carbon capture where currently no storage is included; CBr Brown coal; CBk Black coal; IGCC Integrated gasification combined cycle; OCGT Open cycle gas turbine; SC Supercritical; USC Ultra-supercritical; WC Water-cooled. Source: NEA IEA OECD (2010).



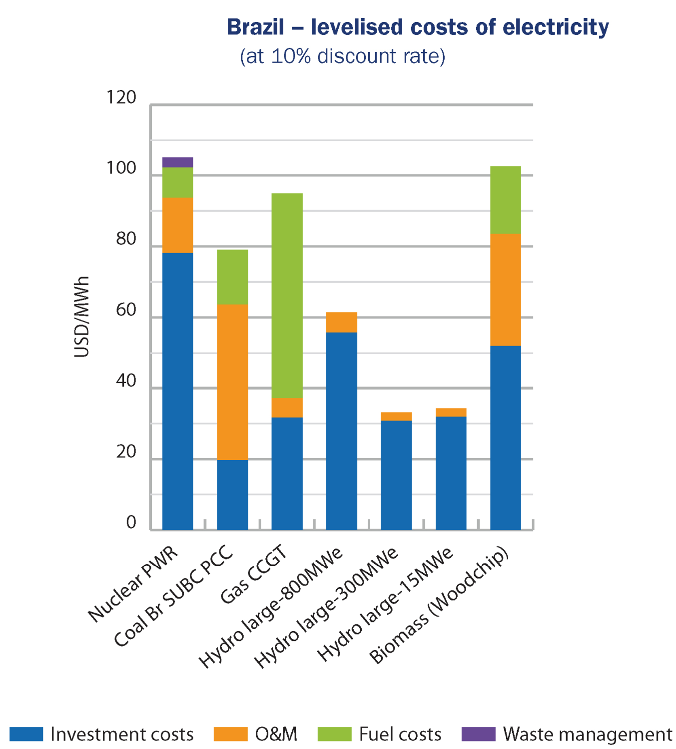


Figure 11: LCOE in Brazil. Key: AC Air-cooled; CCGT Combined cycle gas turbine; PCC Pulverised coal combustion; SUBC Subcritical. Source: NEA IEA OECD (2010).

Unfortunately the graph does not show the LCOE for solar PV, concentrated solar thermal power (CSP) or wind power in Brazil. Therefore this study aims to present a more complete analysis which includes these omitted renewable technologies. Additionally the above graph does not consider the impact of future carbon taxes if implemented in Brazil.

Another interesting study published by the Melbourne Energy Institute (HEARPS & McCONNELL, 2011) reviews the current and future LCOE of wind, photovoltaic and solar thermal energy generation technologies, comparing data from a range of international and Australian studies.

The principle sources reviewed were the:

- European Photovoltaic Industry Association's "Solar Generation 6" 2011 report (EPIA);
- International Energy Agency's "Projected Costs of Generating Electricity" 2010 report (IEA (PCEG)) ;
- International Energy Agency's "Technology Roadmap - Solar Photovoltaic Energy" 2010 report (IEA (RoadMap));
- Global Wind Energy Council's "Global Wind Energy Outlook" 2010 report (GWEC);
- International Energy Agency's "Technology Roadmap - Concentrating Solar Power" 2010 report (IEA);
- Sandia National Laboratories (US Department of Energy's) "Power Tower Cost Reduction Roadmap 2011 report (US DoE);
- AT Kearney Consulting with European Solar Thermal Electricity Association (ESTELA's) "Solar Thermal Electricity 2025" (ATK);
- Australian Electric Power Research Institute's "Australian Energy Generation Technology Costs" 2010 report (EPRI);
- Australian Energy Market Operator's 2010 dataset (AEMO).

The results of the review are shown in figures 12, 13 and 14.

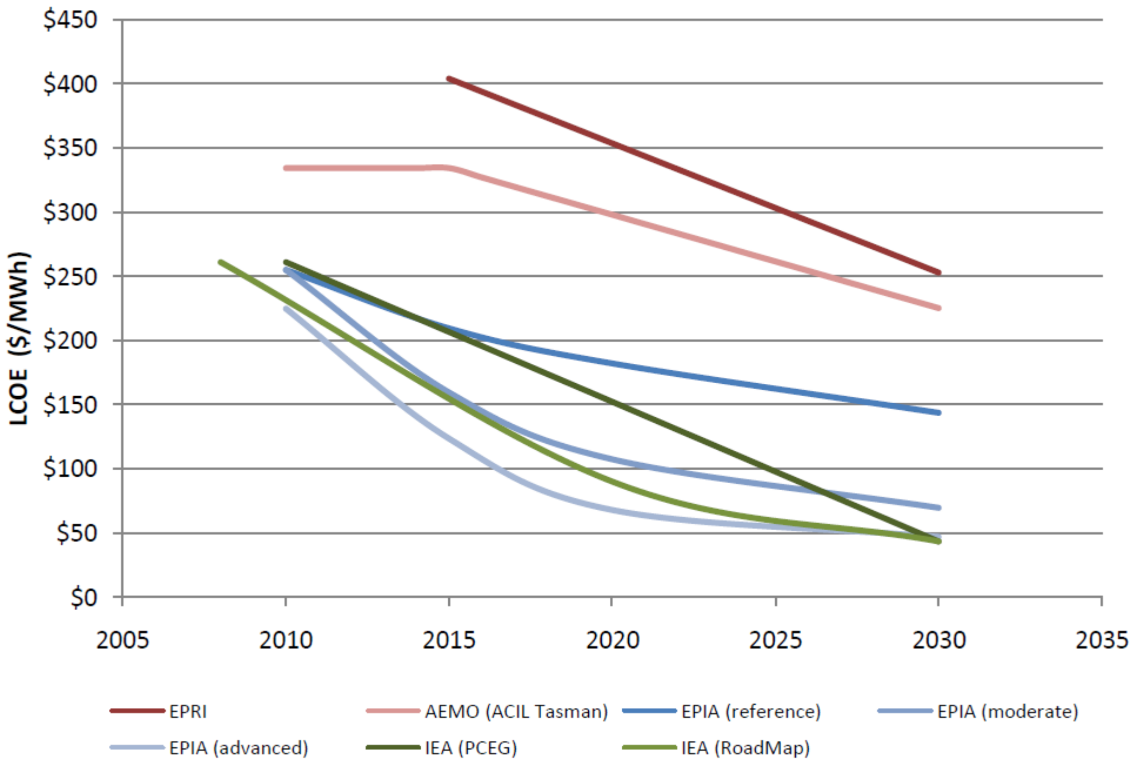


Figure 12: Solar photovoltaic cost projections (Direct Normal Irradiation = 2445 kWh/m^2/yr). Source: Hearps & McConnell (2011).

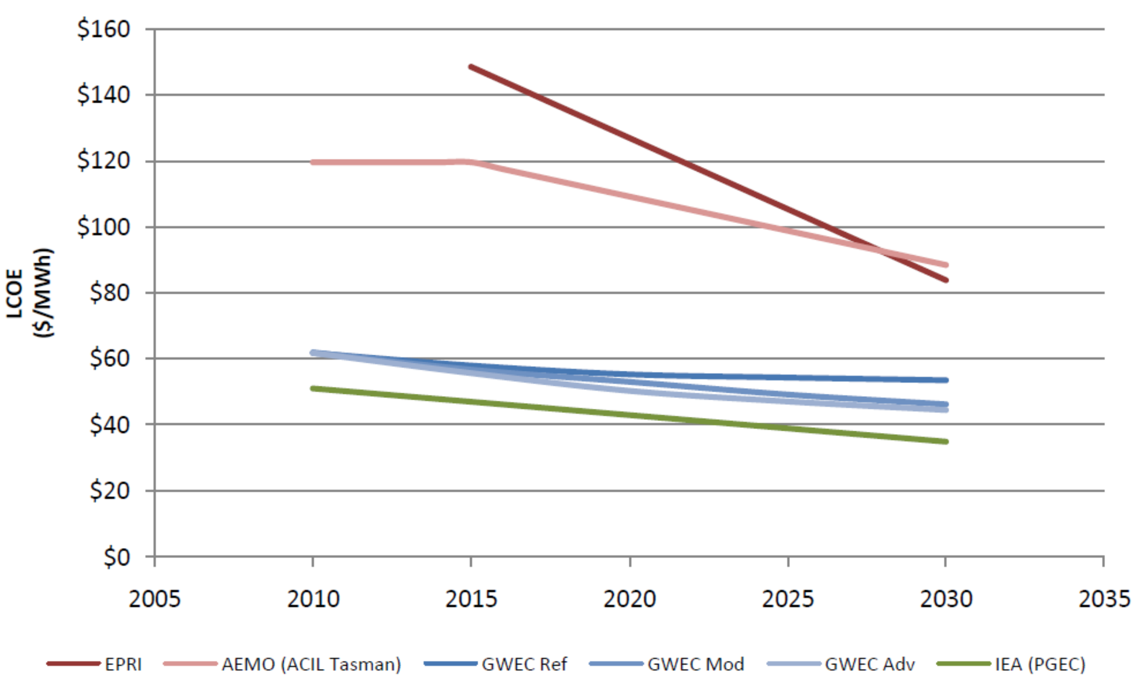


Figure 13: Wind power cost projections. Source: Hearps & McConnell (2011).

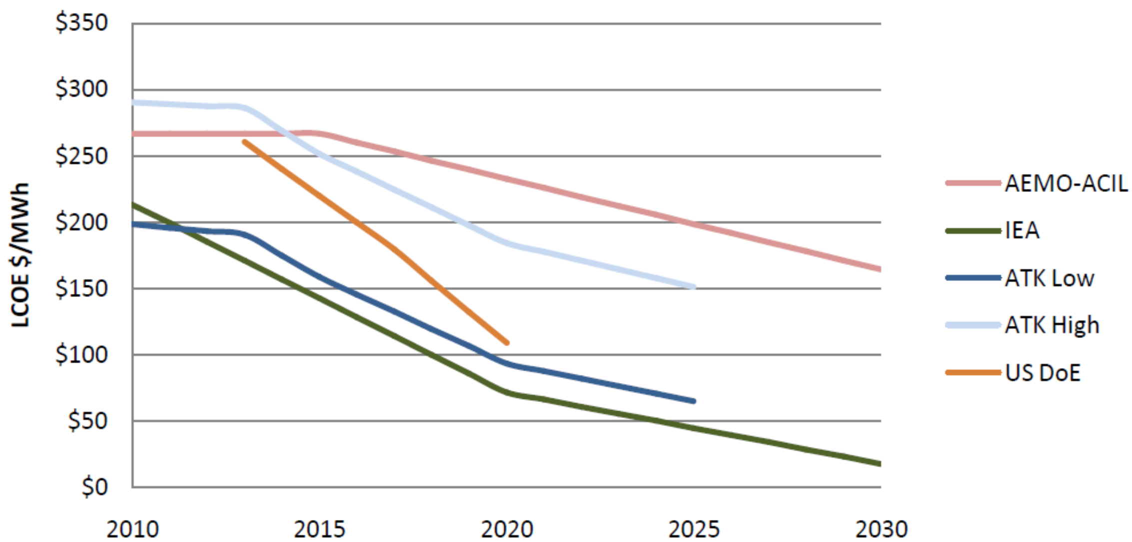


Figure 14: Concentrated solar thermal cost projections, at Direct Normal Irradiation of 2400 kWh/m^2/yr. Source: Hearps & McConnell (2011).

Though, the different studies have differing results in terms of overall LCOE, the trends indicated by all the studies show significant cost reductions by 2030. Solar PV module pricing is projected to decline along a learning curve of 18-22% for each doubling of cumulative capacity. Similarly, according to the IEA curve, the LCOE of CST power is predicted to drop below $50/MWh by 2025. The capital cost of wind is projected to drop at a more moderate rate of 7% for each doubling of cumulative capacity. In contrast, according to Hearps & McConnell (2011) the LCOE of Combined Cycle Gas Turbine generation is predicted to increase while the LCOE for Pulverised Black Coal generation in Australia will decline by less than 10% between 2011 and 2030. However, it should be noted that the LCOE from fossil fuel generation is highly sensitive to fuel prices (which may increase due to increased demands) and the level of carbon taxes as well as future legislation. Though the price of Australian Thermal Coal was relatively flat from 1983 to 2002, the price has increased from $27/tonne in 2002 to $103/tonne in 2012 (IMF, 2013), therefore the predictions that the LCOE from black coal will decline is not consistent with historical data.

Delucchi and Jacobson (2011) argue that all of the world's energy requirements, including electrical, transportation and heating and cooling, could reliably be supplied by wind, water (wave, hydroelectric and geothermal) and solar resources at reasonable cost. The authors outline various techniques that could be used to integrate these renewable technologies into an electricity grid and deal with their unpredictable variability to ensure that supply matches demand. One of these methods is interconnecting variable generation plants (such as wind, solar and tidal power) over geographically dispersed regions. Therefore, as well as reviewing the LCOE for various renewable energy technologies, the article also includes 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 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 (DELUCCHI & JACOBSON, 2011).

5.2. Levelised cost of wave and tidal power compared to other technologies

Allan et al (2011) 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). The other technologies include Pressurised Water Reactor (PWR) Nuclear, Combined Cycle Gas Turbine (CCGT) with and without Carbon Capture and Storage (CCS), Pulverised Fuel black coal (PF coal) - Advanced Super Critical (ASC) with and without CCS, Integrated Gasification Combined Cycle (IGCC) Coal with and without CCS, Retrofit Coal based on PF coal ASC with Flue Gas Desulphurisation and CCS, and On- and Offshore Wind power. The technology with the lowest levelised cost was Pulverised Fuel (black coal) at £26.19/ MWh, and the most expensive non-renewable generation technology was CCGT with CCS at £48.07/MWh. The levelised costs of Onshore and Offshore wind were calculated to be £54.42 and £81.56/MWh, respectively. The levelised costs of Wave and Tidal Stream electricity generation were £189.68 and £81.25/MWh respectively, at 2006 prices and with a discount rate of 10%. The levelised costs of electricity in £/MWh, at 2006 prices, for all the generation technologies, are shown in figure 15.

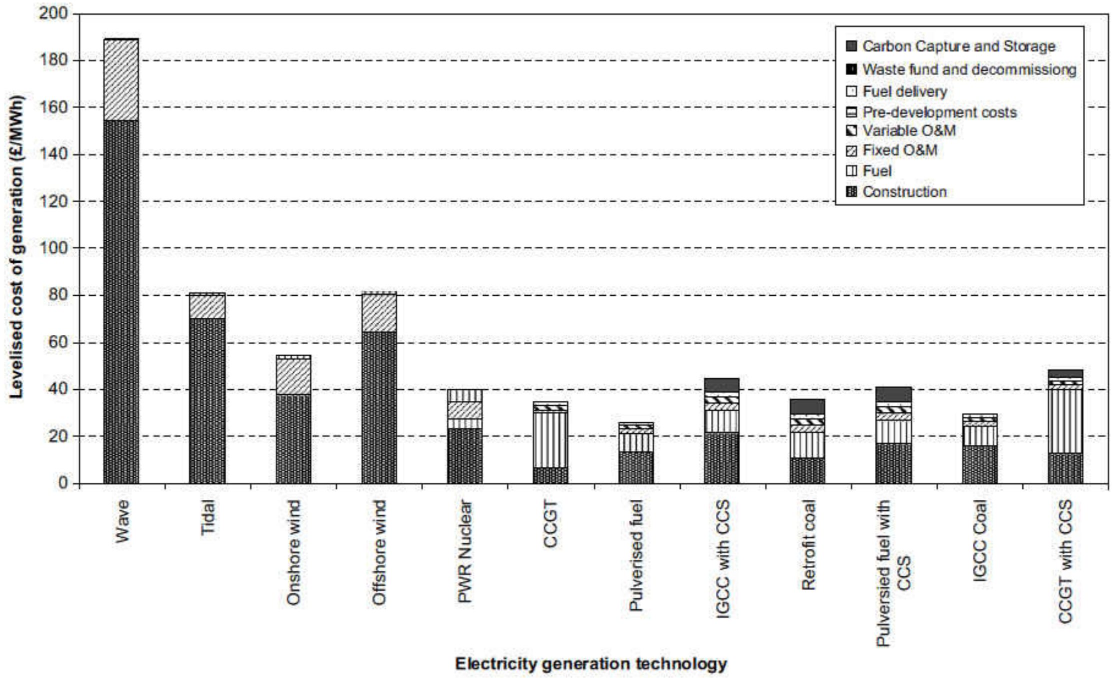


Figure 15: LCOE by source in the UK. Source: Allan et al (2011).

Unfortunately the study does not include any forms of solar electricity generation. Additionally for all the renewable technologies considered a lifetime of only 20 years is assumed compared with that of 50 years for the Pulverised Fuel black coal generation method. This seems to be a frequent bias against renewable technologies. Onshore wind plants can have lifetimes of 35 years or more, however in many LCOE studies a 20 or 25 year lifetime is assumed and this negatively prejudices wind power against traditional technologies such as fossil fuel and nuclear plants.

5.3. Levelised cost of Nuclear power compared to other technologies

Nicholson et al (2012) in their article "*How carbon pricing changes the relative competitiveness of low-carbon baseload generating technologies"*, attempt to make an objective analysis of various authoritative economic studies on the LCOE and life-cycle assessment (LCA) for emissions, of various generation technologies. However the article only considers technologies that can be regarded as 'fit-for-service', that is, low-emission technologies that can supply baseload electricity demands.

According to the authors' method, a technology considered fit-for-service as a baseload generator, needs to be scalable, dispatchable without large storage and have a reliable fuel supply, low or moderate emissions intensity and a high capacity factor. Given their stringent conditions they only consider pulverised fuel black coal with (and without) carbon capture and storage (PF Coal/CCS), integrated gasification combined cycle coal with CCS (IGCC/CCS), combined cycle gas turbine with CCS (CCGT/CCS), nuclear power, and solar thermal with thermal storage and hybrid gas.

Unfortunately the authors do not consider hydroelectricity, biomass, geothermal, wind, PV, wave or tidal energy as eligible to these criteria. Thus the only renewable technology they include in the analysis is solar thermal, which happens to be one of the most expensive technologies compared to all the other renewable technologies which were excluded.

A carbon price will affect the cost of each technology differently due to differences in emission intensity factors. Thus each technology's relative competitiveness can be illustrated by plotting the LCOE against an increasing carbon price. The results can be seen in figure 16.

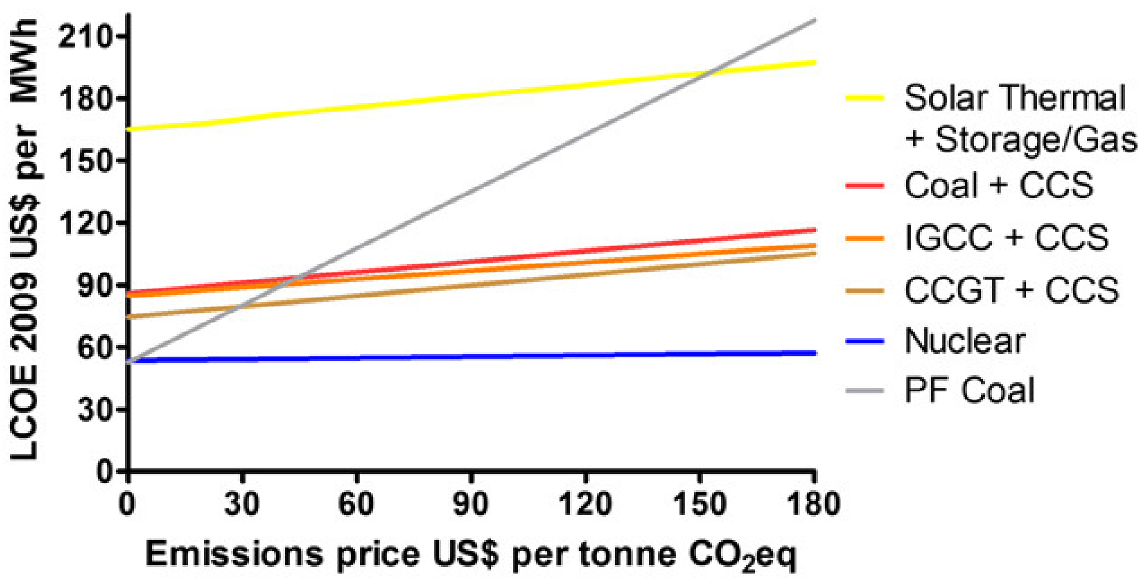


Figure 16: LCOE with carbon taxes. Source: Nicholson et al (2012).

From these results the authors conclude that nuclear power is the most competitive of the studied technologies and also has the lowest emissions intensity. Solar thermal is the most expensive of any of the low-carbon "fit-for-service" technologies regardless of the carbon price and even if its costs could be halved would remain more expensive than nuclear power.

The method used to evaluate the emission intensity and the LCOE with an increasing carbon price is both established and recognised in various studies as a reliable way to compare different technologies.

However it is unfortunate that the study only included solar thermal and did not include other more competitive renewable energy sources. Hydroelectricity, biomass, and conventional geothermal were excluded on the grounds that they are not scalable and because of their supposedly lower capacity factor compared to thermal electricity generation technologies. However, in Brazil for example, both hydroelectricity and biomass have been installed on extremely large scales and can have capacity factors of greater than 80%. Additionally in Iceland geothermal and hydroelectricity supply approximately 30% and 70% of the energy respectively to the electricity matrix. In the USA it is estimated that an additional 80,000MW of environmentally friendly hydroelectric capacity could be developed (KOSNIK, 2008); 59,000MW through new small and micro hydroelectric plants, 17,000MW by installing hydroelectric turbines at existing dams which are currently only used for flood control, navigation or water supply, and 4,000MW via generation efficiency improvements at existing hydroelectric facilities. In total that is equivalent to 80 (1000MW) nuclear power plants. Recently the Danish government adopted a plan to increase the share of electricity production in Denmark from wind to 50% by 2020.

The article references a study by Succar et al (2006), which shows that wind power combined with compressed air energy storage (CAES) will become cost competitive with IGCC/CCS when the carbon price reaches \$100/tonne of carbon (which is actually equivalent to \$27/tonne of CO_2, not \$367/tonne of CO_2 as the authors' incorrectly stated). Contrary to the authors' conclusion, this low carbon price is expected to occur before 2030 and therefore including wind power in the analysis would have been useful.[3] Therefore the argument that all the excluded renewable technologies are not competitive or not fit-for-service as a base-load generator is unsound and these technologies should have been included in the study to allow for a more objective unbiased analysis.

[3] As mentioned earlier, in Australia a carbon tax of \$23 per tonne of CO2eq was implemented on the 1st July, 2012.

The article's conclusion that nuclear power is the standout solution in terms of cost for low emissions base-load electricity is clearly not objective. Interestingly the article was written before the Fukushima meltdown and since then the financial, environmental and health risks associated with nuclear power have been re-evaluated by many governments. Japan shutdown all its nuclear reactors for over 12 months and Germany is planning to permanently decommission all its nuclear plants.

There are also prejudices against renewable energy sources, such as wind power, from conservative lobby groups, government and the media (GOLDENBERG, 2013). Proposed wind farm projects in Australia 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. Residents and landowners lobby to stop construction of wind farms because of the impinged view and claim that noise from wind farms causes health problems despite the fact that there is no scientific evidence for this (SECCOMBE, 2012 and SONUS, 2010).

5.4. The Cost of Energy (COE) for grid connected PV compared to grid only electricity

Thus far none of the studies above consider photovoltaic (PV) solar power. Liu et al (2012) investigated the economic, technical and environmental performance of residential PV system in Queensland (Australia). Using HOMER software the NPC, COE and CO_2 emissions during the lifetime (20 years) of grid connected PV systems with feed-in-tariffs are simulated and optimized for 11 different cities in the state of Queensland.

The results found the optimized configuration was a 6kWp PV system with a fixed slope of 20° to 25° depending on the location.[4] The COE for the optimized PV systems in 9 out of the 11 cities would be less 50% of a grid only residential system of $0.169/kWh. See figure 17, which compares the COE for the 11 cities used in the study.

[4] Note that kWp (kilowatt-peak) values represent the rated capacity of a PV system. However, depending on the average daily solar radiation level, fixed tilt PV systems have capacity factors of 14-24% (NREL, 2011). That is, the average daily output power of a PV system is only 14-24% of its kWp rated capacity.

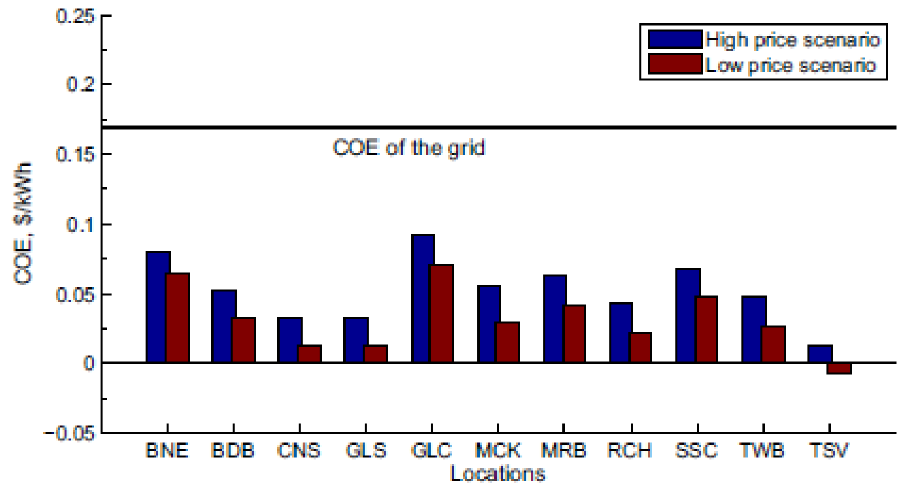


Figure 17: COE of grid connect PV in Queensland Australia. Source: Liu et al (2012).

These 6kWp PV systems would generate from 54 to 61% of a typical residential energy demand (23kWh/day) and would feed 5552 to 6810 kWh of electricity back to the grid per year. Additionally the optimized PV systems would reduce carbon dioxide emission from 7757 kg/year (for a grid only residence) to between 52.7 to 1730 kg/year. Townsville, which has the highest solar irradiation of all the cities studied, had the least NPC and the COE (considering a "Low Price Scenario" of PV) was negative which means the PV system would actually make a net income.

The 11 cities studied in Queensland, Australia, have similar latitudes, climates and solar irradiation to coastal cities from Bahia to Santa Catarina in Brazil.

It should be noted that a PV system of only 1.5kWp (a common domestic sized installation) would actually have a higher COE than a grid only system. The explanation for this result is most likely because for a small PV system most of the energy is consumed by the residence and therefore the COE of the PV system (without surplus energy being bought back by the grid) is slightly higher than the grid tariff. It is only due to the high feed-in-tariff of 44 cents per kWh that enables the medium to large domestic PV systems to be economically competitive.

The study omits to take into consideration that in Australia, PV installations are also eligible for Small-scale Technology Certificates (STCs) which are a type of government rebate with an approximate value of $3000 to $9000 for 1.5kW to 10kWp PV grid connected system installed at an eligible residential or business premises.

Feed-in-tariffs applicable in most Australian states combined with STCs have enable enormous growth in grid connected distributed PV installations in Australia since 2009 as can be seen in figure 18 (APVA, 2011).

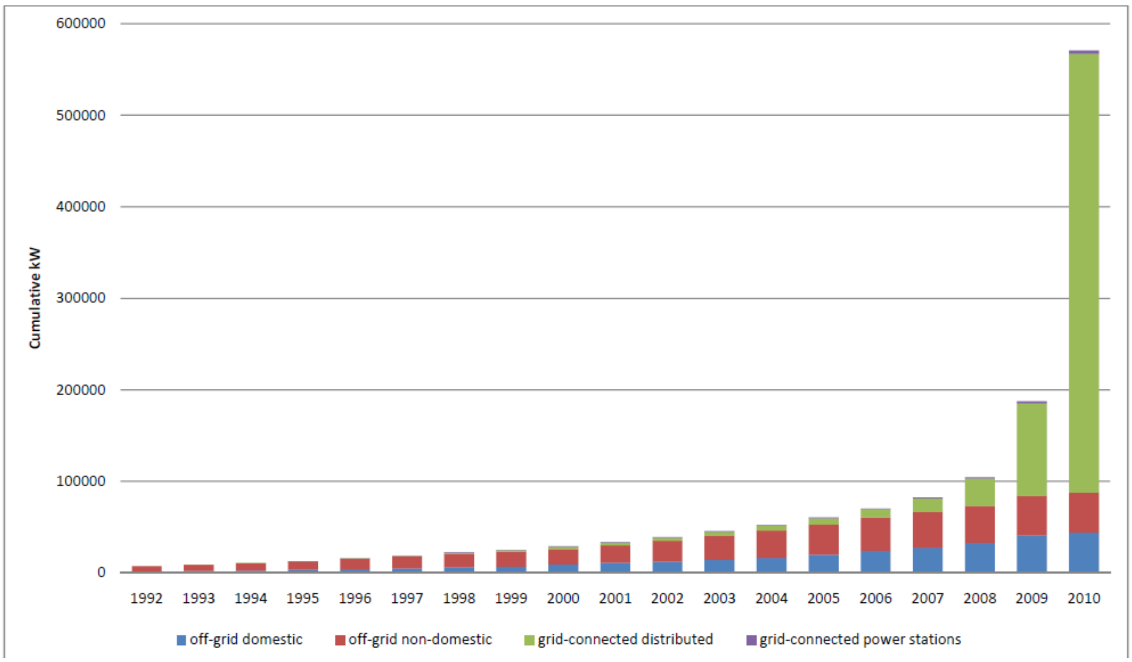


Figure 18: Cumulative PV installations in Australia. Source: APVA (2011).

In 2011, 837MW of PV were installed in Australia, more than double that installed in 2010. Thus as of 2012, there was a total capacity 1400MW of PV installed in Australia of which 88% is grid-connected (APVA, 2012). This is very different to the situation in 2008 where the majority of installations were off-grid systems. However in the second half of 2012, feed-in-tariffs were drastically reduced to approximately 8 cents/kWh in the 3 most populous states in Australia (New South Wales, Victoria and Queensland). This extremely low value is supposed to represent the "actual" value of solar power to electricity system operators. Solar (and wind power) are less valuable to system operators because of their uncontrollable nature compared to other more traditional sources of power generation. This new "feed-in-tariff" rate is approximately one third of the retail price of domestic electricity in Australia. Therefore this effective removal of the financial benefits of feed-in-tariffs will most likely see a large reduction in the amount of new grid connected PV installations in Australia in the coming few years compared to previous years.

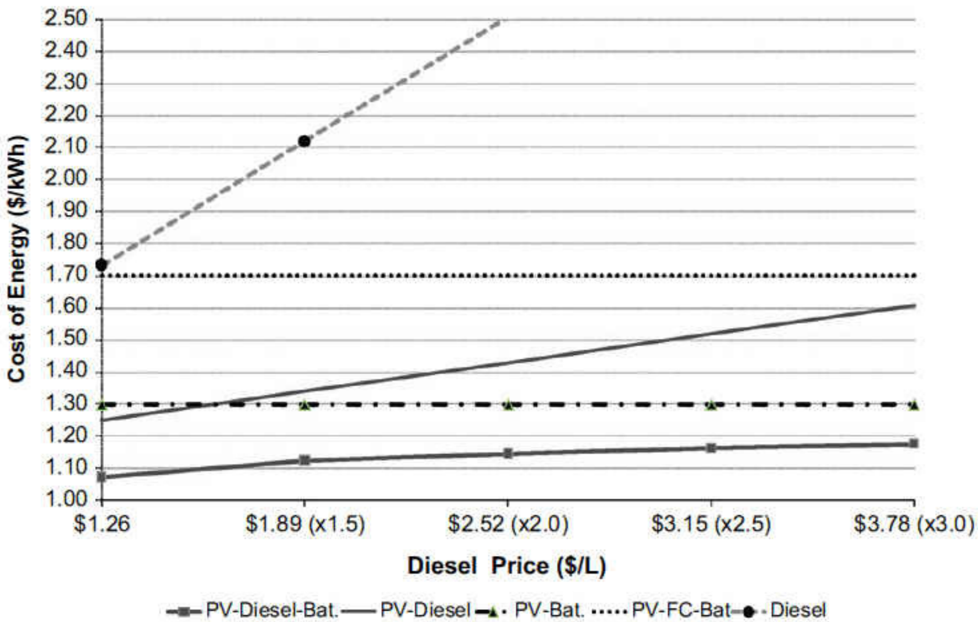
In comparison to Australia, in Brazil currently only 7.6MW of PV is connected to the national grid (ANEEL - BIG, 2013). Australia has almost 200 times more PV installed compared to Brazil which is a country with good solar resources and a population almost 10 times that of Australia. This statistic shows that PV technology in Brazil suffers from a lack of government support and incentives, high import duty and taxes and until recently a lack of regulatory rules that would enable PV to be connected to the national grid.

Considering all the above international studies, it becomes apparent that the LCOE for a particular technology can vary very significantly depending on the country or region. For example coal fired power stations in Australia (not considering carbon costs) have approximately half the LCOE compared to coal fired power stations in Brazil. Similarly, the LCOE of nuclear power in Brazil is more than double that in the Asia Pacific region. On the other hand, the LCOE of large hydro power in Brazil and China is a fraction of that in many other regions (NEA IEA OECD, 2010). The reasons for these variations are twofold. The costs of equipment, fuel and operations and maintenance can vary significantly depending on the region. Additionally the available renewable resources (for example wind speeds, solar irradiation levels, water resources and hydroelectric potential) can also vary greatly depending on the region. Therefore reports such as the IPCC's Special Report on Renewable Energy Sources and Climate (IPCC, 2012) which provides global data on the LCOE for different renewable technologies cannot really be relied upon for accurate LCOE data for a specific region. Hence this study focuses specifically on Brazilian electricity power plants and aims to provide accurate LCOE data for Brazil.

5.5. Previous COE and 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 (2009), presents a map of the *"…Life Cost Saving of Photovoltaic Diesel Hybrid Power Plant for Isolated Grids"* in Brazil where generally good levels of solar irradiation exist. For a single 106kW generator combined with a 79.04kWp PV array, life cost savings of up to $250,000 can be achieved compared to a diesel only generator.

Silva et al (2010) 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. Currently diesel generators are the predominant technology that provides electric power to isolated communities in the Amazon. Fossil fuel used by these diesel generators is often subsidized by the Federal Government through the Isolated Fossil Fuel Consumption Account (CCC-ISOL) and as of 2008 the fossil fuel subsidies covered by CCC-ISOL cost the government $2.51 billion. The greatest barrier to the development of renewable energy systems 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 and often don't consider the lifetime cost of equipment and fuel. The results of the Silva et al (2010) study showed that the system lifetime cost of energy (COE) generated exclusively by diesel generation (at 2009 fuel prices and not allowing for fuel transportation cost) was greater than all the renewable PV energy and hybrid configurations evaluated. In figure 19, the COE is shown as a function of the cost of supplying diesel fuel for the various configurations considered.



Influence of the transportation cost of diesel fuel to isolated Amazon communities for the various HDGS configurations.

Figure 19: COE as a function of the cost of supplying diesel fuel. Source: Silva et al (2010).

Considering the case where diesel transportation costs can actually triple the price of supplying fuel, the COE for both the PV–diesel–batteries and the PV–batteries configurations were less than 40% of the COE for the diesel only generator, at 2009 diesel prices.

There are almost no studies which specifically examine the LCOE for grid connect renewable technologies in Brazil. Cardemil and Colle (2010) conducted one of the few studies examining the economic viability of a concentrated solar thermal power system in Brazil. Using SWERA (Solar and Wind Resource Assessment) data, the study simulated the Levelised Cost of Electricity (LCOE) for a 30 MWe CSP system located in Bom Jesus da Lapa in the Northeast of Brazil based on the SEGS VI plant with and without a hybrid fossil fuel backup system. The study concluded that the LCOE for the CSP system ranged between US$267.5 per MWh (with a hybrid gas heating backup system) and US$378.3 per MWh (without the hybrid backup), and the LCOE was also dependent on the amount of thermal storage and the required capacity factor. In calculating the LCOE, this study assumed a nominal discount rate of 12% in Brazil, and also allowed for an inflation rate of 5%.

5.6. Environment and social impact studies

Emission intensity factors can be obtained by making a life cycle assessment (LCA) of each technology in terms of kg of CO_{2eq} emitted per MWh generated. In the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) produced by The Intergovernmental Panel on Climate Change (IPCC, 2012) 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 (g CO_{2eq}/kWh which is equivalent to kg CO_{2eq}/MWh). Source: IPCC (2012).

Values	Bio-power	Solar		Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
		PV	CSP								
Minimum	-633	5	7	6	0	2	2	1	290	510	675
25th percentile	-360	29	14	20	3	6	8	8	422	722	877
50th percentile	18	46	22	45	4	8	12	16	469	840	1001
75th percentile	37	80	32	57	7	9	20	45	548	907	1130
Maximum	75	217	89	79	43	23	81	220	930	1170	1689
CCS min	-1368								65		98
CCS max	-594								245		396

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

Measuring the environmental and social impact from different generation technologies is a complex task. As can be observed in table 1, fossil fuel plants such as coal fired power stations produce the largest amounts of GHG emissions per MWh and thus cause the most GHG damage to the environment. However various generation technologies including renewable energy technologies can impact the environment in different ways to some degree.

There have been a number of studies that estimate the cost of environmental externalities in terms of GHG damage costs and health impact costs. The most extensive study on the cost of externalities from power generation is the European Union's ExternE Project which was succeeded by NEEDS (New Energy Externalities Development for Sustainability). The Australian Academy of Technological Sciences and Engineering (ATSE, 2009) used the ExternE results and applied them to the Australian electricity generation sector.

Alves and Uturbey (2010) calculated the environment externality costs of electricity generation in Brazil using various sources. For GHG damage costs their study also followed the ExternE methodology for fossil fuel plants (applying a damage cost of \$25/tCO_{2eq}) and followed equations developed by the IPCC for hydroelectric plants. Fearnside (2009) 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 (2010) method to the Belo Monte and Babaquara dams results in a comparative prediction for the quantity of GHG emissions.

Delucchi and Jacobson (2011) 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).

However, it is worth noting that the methodology used by Alves and Uturbey (2010) to calculate the health impacts due to fossil fuel and biomass generation sources differs considerably from the ExternE methodology and only considered particulate matter emissions, but did not consider sulphate dioxide (SO_2) and nitrogen oxides (NO_x) emissions. As a result the health impacts from natural gas-fired plants are not considered. Particulate matter emissions from coal fired power plants, in accordance with current Brazilian legislation, are limited to 1.53 grams/kWh, and were calculated to cause health damage equivalent to \$1265/MWh and \$255/MWh for medium and low density populations respectively (ALVES & UTURBEY, 2010). The results suggest that the extreme health costs due to coal fired power plant particulate pollution renders the technology completely uneconomical. These results are also more than 10 to 100 times higher than the ExternE estimates (which included SO_2 and NO_x emissions) for the cost of health impacts due to local air pollution from coal power plants. These differences in magnitude demonstrate the complex and controversial nature of estimating the cost to society of environmental externalities.

5.7. Renewable resource complementarity studies

There have been a number of studies examining solar and wind resource complementarity and to what extent these resources correlate to peak load demand when connected to the electricity grid. Almeida (1983) used a simple multivariable weather model for the simulation of a combined wind-solar-hydro power system in Portugal, using wind speed (m/s) at a height of 50m, global radiation (kWh/m^2) and rainfall (l/m^2) data. The study calculated both simple and partial correlation coefficients between these three parameters.

Moura (2010) in the article entitled “Multi-objective optimization of a mixed renewable system with demand-side management” studied the correlation between wind, solar and hydro resources in Portugal by presenting the yearly variation curves of their capacity factors.

A study by Hoicka and Rowlands (2011) found that combining renewable energy sources such as wind and solar power in Ontario, Canada, smoothed out power production in terms of reducing instances of high and low values. Additionally, increasing the number of locations geographically of both wind and solar resources further smoothed out power generation and produced less variability. The study did not consider the correlation of wind and solar resources data with variations in the region’s electricity load.

Li et al (2009) examines the correlation of wind and solar resources data against the electricity load curve in NSW, Australia for an entire year. The normalised results showed a strong complementarity between the combined resources of wind and solar source, which also cross correlated to the electricity demand.

Mai et al (2012) simulated hourly production of electricity in the USA for 2050 with nearly 80% of electricity from renewable resources, including nearly 50% from variable renewable generation. The simulations predicted that there would be no hours of unserved load during peak load hours in summer (July) or during any other hour of the year.

Similarly, Elliston et al (2012) demonstrated simulations for 100% renewable energy systems to meet actual hourly demand in the Australian National Electricity Market (NEM) in 2010. They found that various renewable configuration were technically feasible and could meet the NEM supply-demand reliability standard. Technologies included in the simulations were concentrated solar thermal (CST) power with storage, wind, PV, existing hydro and biogas turbines.

Sayeef et al (2012) examined various international studies on the intermittency of wind and solar energy and their correlation with hourly load profiles. Similarly, Burger (2012) shows daily weekly, monthly and annual graphs of planned versus actual production of photovoltaic, wind and conventional energies in Germany.

In Brazil, though wind and solar resource data exists, very little research has been done on the complementarity of these renewable resources combined with existing hydroelectric plants and how they will impact on the electricity grid and the load curve.

A study on integrating wind energy generated in the NE of Brazil into the region's power system by Borba et al (2012) found that by 2030 there would be approximately 6.5% of surplus wind energy between midnight and 6am during the seasons of summer and autumn. The authors propose that this excess energy during the first six months of the year could be used to charge a fleet of plug-in hybrid electric vehicles. However the study does not take into consideration the water savings that could be made by controlling hydroelectricity production during these periods of surplus wind generation. A simple graph of seasonal variations between wind power, hydroelectricity output availability and the NE load curve demonstrates the complementary nature of wind power to large hydroelectricity availability, but the authors do not consider the advantages of this complementarity.

6. MATERIALS AND METHODS

In this section the methods used for the economic, environmental and technical analysis of various electricity generation technologies are explained.

6.1. Economic analysis

There are various methods that can be utilized to assess the economic viability of different generating technologies. Typical financial indicators include net present value (NPV), internal rate of return (IRR) and payback time. However all these methods do not properly consider variation in the size of different projects such as installed capacity and the amount of energy generated per year. Even if an attempt is made to levelise these indicators per MWh of energy generated, usually the revenue per MWh varies across different technologies because different technologies price energy differently. Another economic indicator sometimes used in the electricity industry is the overnight investment costs per kW of installed capacity, however this does not take into consideration differing capacity factors. For example solar PV installations typically produce an average of only 10-20% of their nominal capacity, compared to fossil fuel and nuclear installations which have capacity factors of 80-85%. By including the capacity factor, one could calculate the overnight investment cost per kWaverage generated, but this method still does not consider operating and maintenance costs, fuel costs, carbon taxes, lead times, lifetime of the technology or discount rates.

Therefore, in this study, the costs to produce electricity (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. The cost of electricity or LCOE is calculated by choosing a constant price of electricity that will result in the NPV of the plant equating to zero (or just breaking even). That is, 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 (NEA-IEA-OECD 2010):

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

Then

$$LCOE = P_{Electricity} =$$

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

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. The real interest rate is given by the expression: (1+r) = (1+n)/(1+i). Where "r" is the real interest rate, "n" is the nominal interest rate, and "i" is the Inflation rate. For low levels of inflation it is simpler to use the FISHER EQUATION: r = n – i. That is, it is assumed that the real interest rate is the nominal interest rate less inflation. This method assumes that fuel costs, and operations and maintenance (O & M) costs increase in accordance to the inflation rate.

For each of the projects analysed, specific technical and financial data were collected from publicly available sources. The Project Design Document (UNFCCC, 2010), of Brotas de Macaúbas – is a document by which the Brotas de Macaúbas project was submitted for validation under the Clean Development Mechanism (CDM). Taking the Project Design Document of Brotas de Macaúbas as a base for the development of the wind farm and assuming additional premises from publicly available data sources, the LCOE can be calculated. Given that the Project Design Document of Brotas de Macaúbas presented very detailed technical and financial data, where applicable, this document was consulted as a reference base to extrapolate values for the other renewable projects, only in those cases where financial and carbon credit information for the other projects could not be located.

The NEA-IEA-OECD (2010) *"Projected Costs of Generating Electricity"* publication contains detailed financial cost data on various Brazilian electricity generation technologies. Therefore this document was also used as a source of information to obtain explicit operation & maintenance, decommissioning and fuel costs for the fossil fuel (coal and gas), nuclear, and the hydroelectric power station case studies. It was noted that fuel, and operations and maintenance costs per MWh do not change with the discount rate since they are already shown as a proportion of the total levelised cost. This method assumes fuel costs increase proportionally to the inflation rate. Unfortunately this method does not easily take into consideration the scenario where fuel prices increase above the standard inflation rate.

A carbon price will affect the LCOE of each generation technology by different degrees depending on their emission intensity factors. The mean values (50^{th} percentile) of emission intensity factors from the IPCC (2012) report (highlighted in yellow in table 1 of section 5.6), are used to calculate the contribution that carbon taxes would have on the LCOE of the coal and gas fired power plants. For the hydroelectric plants in the Amazon, emission intensity factors are calculated based on the method by Alves & Uturbey (2010) and data from Fearnside (2009). It was assumed that only those technologies that produced more than 50kg of CO_{2eq} per MWh would be subject to carbon taxes. Simply by multiplying the emission intensity factors (in tonnes of CO_{2eq}/MWh) by a chosen carbon tax rate in US dollars per tonne of CO_{2eq}, the cost component of carbon taxes to the LCOE (in $/MWh) can be calculated. The additional cost that carbon taxes would make to the LCOE was calculated for various carbon tax rates up to $300/ ton of CO_{2eq}. In the case where CCS is not viable or widely implemented, a carbon price of $300/t$CO_2$ would be required to achieve the IEA (2010) BLUE Map scenario (in which 2005 emission levels are halved by 2050).

Carbon credits were calculated for those clean renewable energy projects that could be eligible for credits under the CDM. According to the Project Design Document of Brotas de Macaúbas, a clean energy ("zero" emissions) power plant in Brazil would prevent 0.2055 tonnes of CO_{2eq} emission per MWh that it generated (UNFCCC, 2010). Therefore this overall emissions factor for the Brazilian electricity matrix (of 0.2055tCO_{2eq}/MWh) was used to calculate the carbon credits for the eligible clean energy projects at various carbon prices.

6.2. Environmental and social analysis

This study estimates the cost of social and environmental impacts based on data from existing literature. Specifically, following the method used by ATSE (2009) this study uses the findings from the ExternE project 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 for health impact costs and applies them to the Brazilian thermal electric generation case studies.

The annual quantity of GHG emissions caused by the Belo Monte hydroelectric dams and the Santo Antonio dam were estimated according to Fearnside (2009) and Alves & Uturbey (2010). These annual GHG emission predictions were used to calculate the GHG damage costs per MWh following the ExternE and ATSE (2009) methodology.

Extended transmission system losses and costs for the hydroelectric plants are estimates following the results by Delucchi and Jacobson (2011). The energy losses resulting from the extended transmission systems for both the Belo Monte and the Santo Antonio 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 a 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.

6.3. Technical analysis

The technical analysis is based on a statistical study of variables that define wind and solar resources, and their correlation with the load curve and the hydroelectric reservoir volume levels. The parameters chosen to characterize the availability of renewable energies are global solar irradiation on a horizontal surface (kWh/m^2) and wind speed at 10m height (m/s). Extensive sampled data of these parameters were consulted in detail for the studied region. The specific location chosen for the meteorological data was the Metropolitan Region of Salvador (MRS) in the state of Bahia, however the parameters are extrapolated to represent the Northeast coastal areas, and therefore load curves and reservoir volume level data from the whole Northeast region were considered.

With a population of 3.9 million, the Metropolitan Region of Salvador is the largest population centre in the NE and includes a very active industrial area within its limits. It is worth noting that MRS is not one of the most privileged areas in terms of wind resources, but has a wind pattern similar in seasonal variation to the Metropolitan Region of Recife, which is the second largest metropolitan area in the Northeast. Altogether, these two metropolitan areas represent 40% of the total electricity consumption of the Northeast region and their demand behaviour is quite similar to the overall load profile considered in the statistical study (GODOY, 2006 and ONS, 2008).

The wind speed data represents a particular geographical area and depends on several factors (roughness of surface, relief, micro-regions with particular wind patterns). The representative area is smaller than in the case of solar, and is restricted to the surroundings of the data collection weather-station. The wind maps consulted in this research including the "Atlas de Potencial Eólico da Bahia" (COELBA, 2003) and "Atlas de Potencial Eólico do Brasil" (AMARANTE et al, 2001) show a wide area of homogeneous values for average wind speed that stretches up from the MRS along a large portion of the coast.

The global solar radiation offers a much bigger representative area. The yearly variation of this parameter for the MRS is similar to the whole of the Northeast and Southeast coastlines (as can be observed in figure 5). However the MRS has one of the highest annual rainfall totals in the Northeast, and dryer locations away from the coast would be more suitable for solar facilities. Studies on the spatial variability of solar resources in phytogeographic homogeneous regions show that daily global radiation and monthly averages can be extrapolated up to 200 km away with errors of the order of 15% with a confidence level of 90% (GALLEGOS and LOPARDO, 1998).

For solar radiation data, measurements from SINDA - Sistema Nacional de Dados Ambientais - were used. SINDA is a Brazilian network of automatic weather-stations for environmental data collection (INPE, 2012). The automatic weather station located in Salvador (Bahia) measures solar radiation on a horizontal plane (sun plus sky radiation) every minute with a LiCor pyranometer, logs the data, calculates the mean value every three hours and then transmits it to a satellite. The sensor accuracy is ±5% if properly calibrated against an Eppley Precision Spectral Pyranometer (PSP) and recalibrated every two years. For this research, the arithmetic mean value for solar radiation was calculated for each month, from September 1998 to May 2009.

Other solar radiation databases for the chosen location were consulted during the preparation of this research. The "Atlas Solarimétrico do Brasil"/Brazilian Solarimetric Atlas (TIBA et al, 2001) uses a set of Campbell-Stokes-type heliographs for direct solar radiation measurement, while the NASA Surface Meteorology and Solar Energy Dataset (RETScreen Climate Database, 2012) use satellite measurement.

Even though the difference between the measurements of these three databases does not exceed 5% of the measured values, the SINDA Database was considered more accurate and its data was chosen for the monthly mean calculation, because of the quality of the measurement equipment, the regularity of periodic calibrations and because the SINDA Database had the longest measurement log.

Wind speed data at a height of 10m was collected by a tower mounted measuring device at the Millennium Inorganic Chemicals industrial facilities located in Camaçari, MRS. The measurement instrument was an anemometer (wind tunnel-calibrated anemometer with ±1.5% accuracy) and all measurement readings (one every 15 minutes) were considered during the whole year of 2001. In order to assure that the wind pattern during that year had a similar behaviour to other years, other databases were consulted including the "Atlas do Potencial Eólico da Bahia", "Atlas do Potencial Eólico do Brasil" and also measurements from the same tower in the Millennium facilities for the years 1999, 2000 and 2002 (MILLENNIUM, 2002). More recent data at the same location was not available. Wind speed data for 2001 was the most complete dataset and had the least anomalies compared to the other years of available data. The SINDA database also has wind speed data at 10m height for the same year and location (mean values every three hours), so all data records were compared with the purpose of replacing outliers and missing values.

The load profile, which is the curve that shows the variation of the electrical power demand over periods of time, is available for the considered region, for periods of 24 hours and 12 months. This load curve is calculated by the ONS - Brazil's Electrical Grid Operator - which has records of load curves for the last several years. The 12 month load curve profile was calculated as the mean from the last 13 years of load curves, using monthly mean values of electrical power demand measured by the ONS. The accuracy of the power demand measurement is approximately ±0.8% according to the ONS' four-monthly revisions of demand projections (ONS, 2010).

The ONS also maintains a historical record of reservoir volume levels for each region in Brazil, due to the importance of hydroelectricity in the national energy matrix. Based on the measurements of the last 13 years, the mean curve that shows the annual variation of the water volume level in the NE region's reservoirs was calculated. But the time period of the research can be extended by considering the years before the big hydroelectric complexes were built. By focusing only on the São Francisco River, it is possible to calculate the mean values of its monthly flow rate for the entire period from 1931 to 2010, as there are complete flow records for these years at the locations where the main dams were built (ONS, 2011c).

Once a reliable data base of electricity demand and renewable energy parameters was collected, a statistical study was carried out. The average monthly wind speeds and solar radiation levels from the datasets were normalized to their annual maximum values respectively. The NE's average reservoir volume level profile was normalized to the maximum reservoir capacity. The NE's annual load curves were first normalized and the average calculated. Then the correlation coefficients between the datasets were calculated using Minitab software.

The Pearson product-moment correlation coefficient (hereafter Pearson correlation coefficient) ranges from -1 to 1. When comparing two sets of data (X and Y), a value of 1 implies that a linear equation describes the relationship between X and Y perfectly, with all data points lying on a line for which Y increases as X increases. A value of -1 implies that all data points lie on a line for which Y decreases as X increases. A value of 0 implies that there is no linear correlation between the variables.

By comparing two sets of data at a time (Solar vs. Demand, Wind vs. Demand, Solar + Wind vs. Demand; Solar + Wind vs. Reservoir volume levels and water flow rate, separately and together) a study of the relationship between the average monthly values of these parameters that characterize solar, wind, hydroelectric resources and electric demand during a typical year, can be carried out. The renewable energy system (Solar + Wind) that considers the combination of solar and wind resources assumes 50% solar and 50% wind power by calculating the mean value between the normalized solar and normalized wind average monthly values during a typical year.

The Pearson correlation coefficient indicates the strength of the linear relationship between two data sets (which may exist even if one is a nonlinear function of the other), but its value generally does not completely characterize their relationship. A visual examination of the data sets also proves to be useful, so graphs demonstrating the variations of the parameters during a typical year are shown with the aim of complementing the statistical calculation of Pearson correlation coefficients.

7. THE CASE STUDIES

In this section the 13 case studies used in this thesis are outlined.

7.1. 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 and 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 (UNFCCC, 2010).

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% (Renova Energia, 2012).

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, but it is a big step for Brazil where previously solar power has been limited to small scale installation mostly in isolated regions. Consisting of 4,680 photovoltaic panels, which receive the sun's energy and transform it into electricity, the project received an investment of about $5 million. The Inter-American Development Bank has supported the project, unprecedented in Brazil, with an amount of US$ 700,000. According to MPX, the Tauá plant should generate 9,000 direct jobs (MPX Energia, 2012).

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. The installation on the roof of the Pituaçu stadium was very complex requiring adjustments to the existing structures resulting in an above average installation cost (COELBA - Grupo Neoenergia, 2012). The system will supply energy to the stadium and is also connected to the national grid. Excess energy that is generated by the system will be fed into the national grid and credited back to the stadium via ANEEL’s Energy Clearing System legislation introduced in 2012 (see section 4.1 above). This will result in Pituaçu savings of about $59,400 per year in energy expenses.

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 (ANEEL - BIG, 2013), has an installed capacity of 53 MW and the project had a total investment of approximately $92 million (SEPLANDE, 2013). It is the largest sugar cane bagasse biomass power plant in the Northeast of Brazil, (though there are larger biomass plants that use other fuels such as the black liquor power plants in Bahia). 30 MW of the total capacity will be exported to the national grid and the remaining capacity will be used internally by the sugar cane ethanol production plant. The capacity factor was assumed to be 85% (the same as for the coal fired power stations).

Bom Jesus da Lapa CSP (simulation)

On the 11th November, 2011, the governor of Paraíba, the mayor of Coremas and a representative of Rio Alto Energia signed an agreement to install a 50 MW CSP plant in Coremas, Paraíba at an estimated cost of $173 million (GOVERNO DO ESTADO DA PARAÍBA, 2011), however to date it appears that the project has not developed any further. Currently there are still no examples of CSP plants existing or under construction in Brazil. Therefore for this new technology economic data was taken from the article entitled *"SWERA Database as support for techno-economic analysis of solar energy technologies"* (CARDEMIL and COLLE, 2010). 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 relevant economic and generation data from the simulation were extracted from the article and used in this study to calculate the LCOE according to the NEA-IEA-OECD (2010) methodology. The model chosen for the analysis would have no thermal storage capabilities, therefore a conservative capacity factor of 20% was assumed.

7.2. Brazilian Hydroelectric Case Studies in the Amazon

Belo Monte hydroelectric power station

The Belo Monte hydroelectric power station currently under construction in the state of Pará is one of the most controversial energy projects in Brazil because of social and environmental impacts 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 due to the Xingu River having 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 (ELETROSUL, 2010).

A number of adjustments, including a reduced reservoir area, were made to the original design in order to meet current environmental requirements. As for the additional costs due to these requirements, according to cost analysis data from the Energy Research Company (EPE, 2011c), approximately 16% of the total investment required to build the Belo Monte Hydroelectric Plant will be put to social and environmental programs. However the reduced reservoir area also reduced the energy availability and efficiency of the project compared to other hydroelectric installations.

Santo Antonio hydroelectric plant

The Santo Antonio 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% (SANTO ANTÔNIO ENERGIA, 2012). 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. That is, the horizontal bulb turbines rely on the flow of the river and do not require a large head of water to move the turbines. Without the need for a large head, this technology allows for a greatly reduced reservoir area. (The Santo Antonio plant will be one of two Brazilian hydroelectric plants on the Madeira River. The second plant is Jirau with a capacity of 3750MW. Two additional hydroelectric plants will be built on the Bolivian section of the Madeira River).

7.3. Brazilian Fossil Fuel and Nuclear Energy Case Studies

Angra-3 Pressurised water reactor (PWR) nuclear reactor

Angra 3 nuclear power station will be Brazil's third and largest nuclear reactor and is located in Angra dos Reis in the state of Rio de Janeiro. 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 in 2010 and the reactor is expected to go into operation in December 2015 (ELETROBRAS ELETRONUCLEAR, 2012).

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. Both plants will be running on pulverized coal, imported from Colombia, via Pecém Port with a capacity factor of 85% (MPX ENERGIA, 2012).

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 (MPX ENERGIA, 2012). MPX have not explicitly stated that this "clean" coal power station will have carbon collection and sequestration (CCS), however the LCOE analysis (sections 8, 9, 10 and 12) 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 (MPX ENERGIA, 2012).

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 (MPX ENERGIA, 2012). A capacity factor of 80% was assumed for both gas fired power stations.

8. FINANCIAL AND TECHNICAL INFORMATION COLLECTED

Input data including total investment, operations and maintenance, fuel, and carbon 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 Reais to US dollars).

Currently there are no examples of commercial scale wave power plants or concentrated solar thermal power (CSP) installations operating in Brazil. There is a small wave power plant installed in Pecém Port, Ceará, however this is a prototype plant and no economic data is available. Therefore additional LCOE data from international studies for wave power and CSP technologies was considered in the overall analysis. LCOE data from the USA Electric Power Research Institute (EPRI) for an 80MW CSP system was taken from the NEA IEA OECD's "Projected Costs of Generating Electricity" (2010) report and LCOE data for a 10MW wave power plant being developed in Sweden was taken from the same source. Additionally LCOE data for wave power in the UK was taken from the "Levelised costs of Wave and Tidal energy in the UK…" study by Allan et al (2011). (An exchange rate of US$1 = £0.65 (May 2013) was used to convert British Pounds to US dollars). It should be emphasized that these 3 international evaluations of the LCOE of CSP and wave power technologies can only be taken as indicative estimates of the cost of these technologies if properly developed in Brazil. That is, these international evaluations are taken from countries where the technologies are already quite mature. In all likelihood, to develop these new technologies in Brazil there would be added learning curve costs and equipment and skill would probably need to be imported also adding substantially to the capital costs. Therefore initially in Brazil, the LCOE of CSP and wave power generation could be substantially higher than for these other regions, at least until these technologies reached maturity.

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	$/MWh	68.81	72.25	39.09	38.61	no data	73.59	no data	no data	*61.88*	61.88	no data	*creditted*	no data
Investment Cost	**$ 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 $kW_{average}$ 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)	$tCO2_{eq}/MWh$	**0.2055**	0.2055			**0.2055**						**0.2055**	0.2055	**0.2055**
$CO2_{eq}$ emissions (SRREN, 2012)	$kgCO2_{eq}/MWh$	12	12	**287**	33	18	16	**100**	**1,001**	**469**	**469**	46	46	22
$CO2_{eq}$ emissions(+) / credits(-) per year	tCO_{eq}/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**

Table 2: Case study input data.

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" (2010). 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 (2010) 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 (UNFCCC, 2010). 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 red 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 (2009).

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" (2010) report were used.

Exchange rates: For Brazilian data taken from the NEA-IEA-OECD report (2010), 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 to convert Reais to US dollars. Then a rate of US$1 = R$2.02 (for May 2013) was used to convert back to US dollars.

The real LCOE for each case study was calculated for low and high real interest rate scenarios. The median nominal (Selic) interest rate in Brazil during the last 24 months was 10.9% (BANCO CENTRAL DO BRASIL, 2012). The average inflation rate in Brazil during the same period was 5.9% (IBGE, 2012). Therefore the real interest rate over the last 2 years was approximately 5% and this rate was used to calculate the real LCOE for the low discount rate scenario.

At times during the past decade in Brazil inflation and the nominal interest rate reached levels much higher than in countries with developed stable economies. For example in 2003 the inflation rate and nominal interest rate reached highs of approximately 16% and 26% respectively due to uncertainties in the economy (IBGE, 2012 and BANCO CENTRAL DO BRASIL, 2012). Therefore in 2003 (which was an economic period in Brazil with high financial risk) the real interest rate was approximately 10% and this rate was used to calculate the real LCOE for the high discount rate scenario. Thus, this second scenario assumes that the case study projects are subject to high financial risks.

9. LCOE RESULTS

This section details the LCOE results considering four different scenarios including, a low discount rate with and without carbon credits and taxes, and a high discount rate with and without carbon credits and taxes. The various results for the different case studies are compared and discussed.

9.1. Low discount rate scenario without carbon credits or taxes

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 20, shows the LCOE separated by component costs for all the Brazilian case studies (with the exception of the solar power projects).

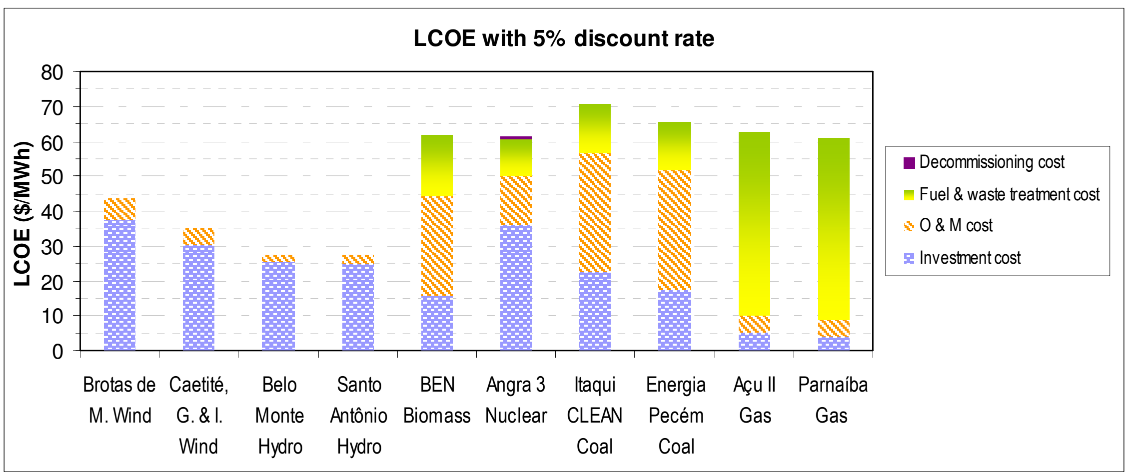


Figure 20: LCOE with low discount rate scenario.

Figure 21, shows the LCOE separated by component costs for the Brazilian PV and CSP case studies, and for the international CSP and wave power projects.

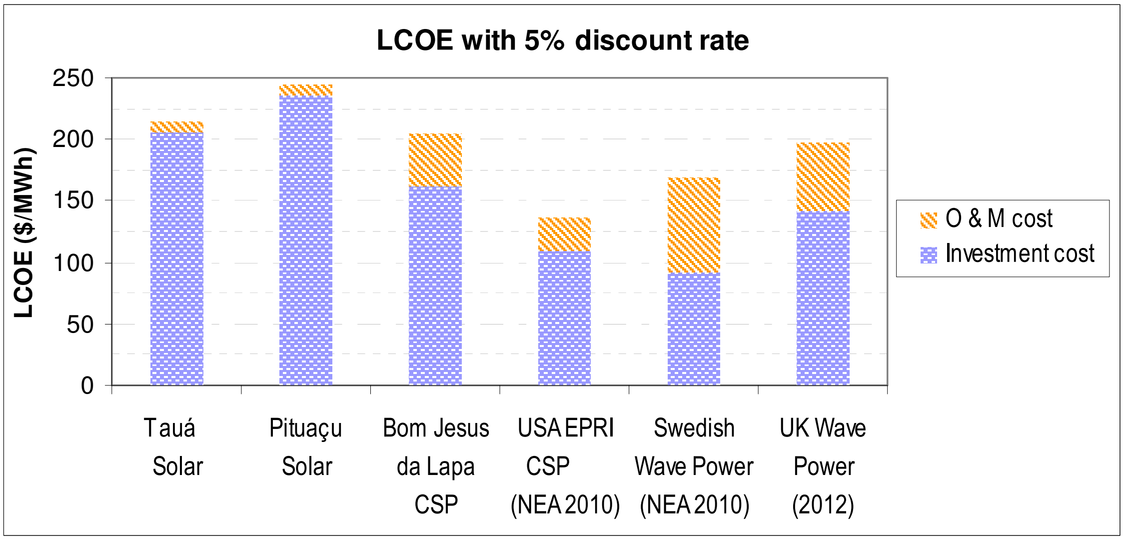


Figure 21: LCOE with low discount rate scenario.

First considering the results using a 5% discount rate without the influence of carbon taxes, 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 carbon capture and sequestration (CCS) equipment.

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 (2010) report, the USA EPRI CSP plant was the 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 (2010) report. Though not considered in the above comparison it is worth mentioning that the Australian wave power plant, discussed in section 11 of this thesis, was only marginally more expensive than the Swedish plant, with a LCOE of $172/MWh, but has a far better capacity factor of 56%. 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 (2003) compares the cost of generating electricity from wave, wind, hydro, solar and thermo combustible, and claim that, at utility scale, theoretically wave energy 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 to be implemented at the end of 2012 will allow PV systems to be connected to the electricity grid and any excess energy not used by the premises of the installation 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, 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 (COELBA, 2012). 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. The gross profit margin for a PV installation at a commercial premise would be of 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 energy (agreed in the national auction of electricity generation licences). The gross profit margins, for those case study projects where wholesale energy price data was available, are shown in table 3.

9.2. Low discount rate scenario with carbon credits and taxes

Table 3 shows the total LCOE for all the case studies using a real discount rate of 5% with and without the influence of carbon credits and taxes. That is, the total LCOE is first calculated to reflect the current situation in Brazil where all the case study projects (with the exception of Brotas de Macaúbas) are not subject to a carbon price. The Brotas de Macaúbas wind farm is the only project currently approved to receive carbon credits and this carbon credit (at the current carbon price of €7.99 or \$10.38/tCO_{2eq} (POINT CARBON, 2012)) is considered in the total LCOE (current situation) for that project.

The impact of carbon credits and carbon taxes is then taken into consideration for each of the case studies. It was assumed that in addition to the Brotas de Macaúbas wind farm, the BEN biomass plant, the Tauá solar (PV) plant, the CSP examples and the wave power examples would all be eligible for carbon credits at the same emissions factor as that used for Brotas de Macaúbas. That is, all these projects save 0.2055tCO_{2eq}/MWh that they produce. In contrast, carbon credits were not considered for Pituaçu solar because of the project's small size and were also not considered for the Caetité, Guanambi and Igaporã wind farm complex, because this project appears to be economically viable without the support of the CDM. It was assumed that the dirty technologies, the coal plants, the gas plants and also Belo Monte which are the projects that produce significant amounts of CO_{2eq} per MWh generated (more than 50kg of CO_{2eq}/MWh) would be subject to carbon taxes. Then the LCOE component as a result of carbon credit / taxes of \$100, \$200 and \$300 per ton of CO_{2eq} was calculated.

Finally, for each of the case studies, the LCOE totals, considering carbon prices of \$100, \$200 and \$300 per ton of CO_{2eq} are shown in the last 3 lines of table 3. In figure 22, the LCOE is shown graphically using a 5% discount rate, with a carbon price increasing from \$0 - \$300/tCO_{2eq}.

Table 3: LCOE for all the case studies, using a real discount rate of 5%, with and without the influence of carbon credits and taxes.

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	25.42	25.17	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	2.20	2.23	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	$/MWh	-2.13		-	-	-	-	-	-	-	-	-	-	-	-		-
TOTAL LCOE (current situation in Brazil)	**$/MWh**	**41.67**	**35.07**	**27.62**	**27.41**	**61.71**	**61.38**	**70.70**	**65.63**	**62.49**	**61.14**	**214.37**	**244.17**	**205.21**	**136.16**	**168.75**	**197.07**
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%**						
Carbon credit / tax at $100/ton of CO2eq	$/MWh	-20.55	0.00	28.65	0.00	-20.55	0.00	10.01	100.10	46.90	46.90	-20.55	0.00	-20.55	-20.55	-20.55	-20.55
LCOE with Carbon price of $100/tCO2eq	**$/MWh**	**23.25**	**35.07**	**56.28**	**27.41**	**41.16**	**61.38**	**80.71**	**165.73**	**109.39**	**108.04**	**193.82**	**244.17**	**184.66**	**115.61**	**148.20**	**176.52**
LCOE with Carbon price of $200/tCO2eq	**$/MWh**	**2.70**	**35.07**	**84.93**	**27.41**	**20.61**	**61.38**	**90.72**	**265.83**	**156.29**	**154.94**	**173.27**	**244.17**	**164.11**	**95.06**	**127.65**	**155.97**
LCOE with Carbon price of $300/tCO2eq	**$/MWh**	**-17.85**	**35.07**	**113.59**	**27.41**	**0.06**	**61.38**	**100.73**	**365.93**	**203.19**	**201.84**	**152.72**	**244.17**	**143.56**	**74.51**	**107.10**	**135.42**

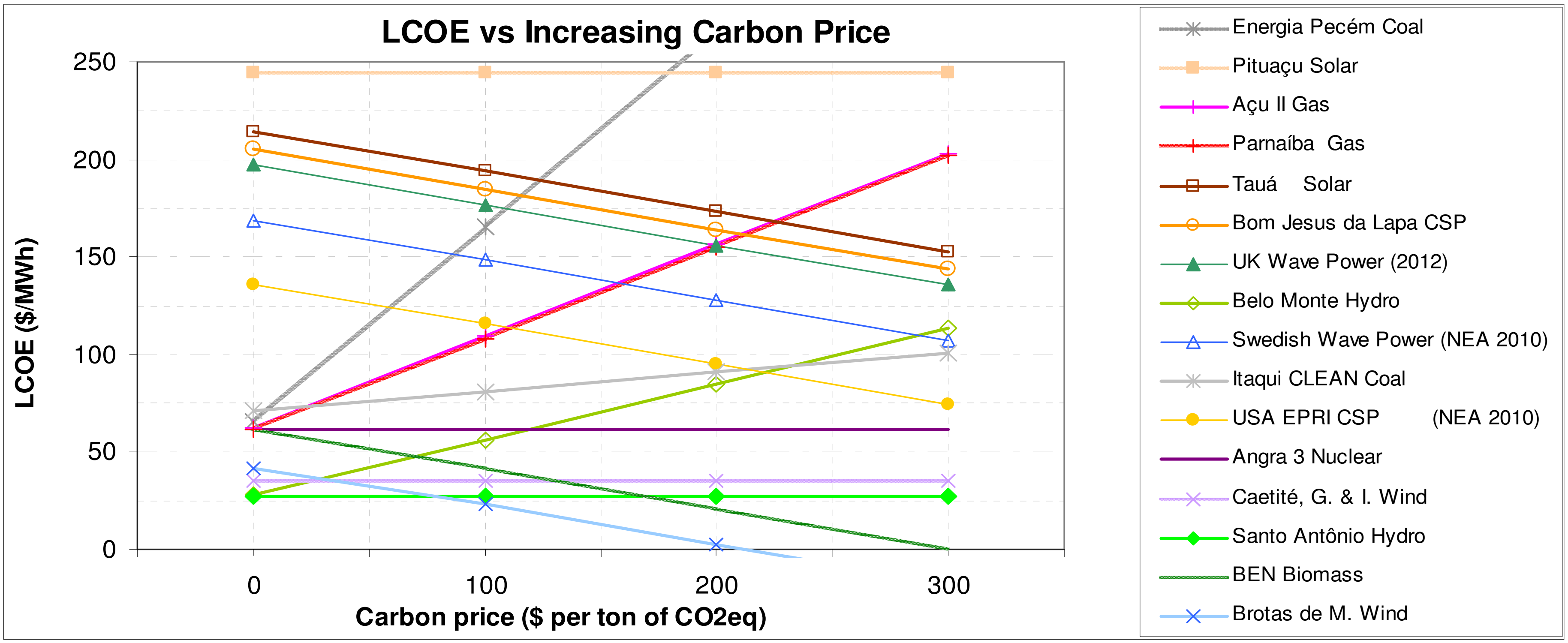


Figure 22: LCOE shown graphically at a 5% discount rate with a carbon price increasing from $0 - $300/tCO$_{2eq}$.

Considering the results with carbon credits and taxes, the LCOE varies depending on the technology and depending on the level of the carbon price. This is best illustrated in the graph shown above in figure 22. If for example, the line of project “X” crosses the line of project “Y” to a higher LCOE value, then this signifies that project X becomes more expensive than project Y at that specific carbon price.

For example, with a carbon price above about $10 per ton of CO_{2eq}, the Itaqui “Clean” Coal power station begins to be more competitive than the Pecém coal plant without CCS technology, but it is not competitive with the gas plants until the carbon price is above $25 per ton of CO_{2eq}. With the exception of Pituaçu PV, above $125 per ton of CO_{2eq}, the Pecém coal plant without CCS becomes more expensive than all the renewable technologies considered, including the Tauá PV case study. Also at about $125 per ton of CO_{2eq}, the gas technologies are already more expensive than the USA EPRI CSP plant.

However even with a carbon price of $200 per ton of CO_{2eq}, the Brazilian solar PV and CSP case studies all have a LCOE above $160/MWh, and thus would still be slightly more expensive than the gas plants and uncompetitive compared to the hydroelectric, wind, biomass, nuclear and clean coal technologies.

Assuming that the Belo Monte plant would be subject to carbon taxes due to the impact caused by methane emissions from the Belo Monte and Babaquara reservoirs, then above a carbon price of R$30 per ton of CO_{2eq}, Belo Monte becomes more expensive than both the Caetité/Guanambi/Igaporã wind farm complex and the Brotas de Macaúbas wind farm. Above a carbon price of $75 per ton of CO_{2eq}, the Brotas de Macaúbas wind farm becomes the most competitive project, even cheaper than the cleaner hydroelectricity plant of Santo Antonio.

9.3. High discount rate scenario without carbon credits or taxes

As per the method with the low discount rate scenario, the LCOE was calculated for the high discount rate scenario using a real interest rate of 10% for all the Brazilian case studies considered and also for the international examples of CSP and wave power technologies. Figure 23, shows the LCOE separated by component costs for all the Brazilian case studies (with the exception of the solar power projects).

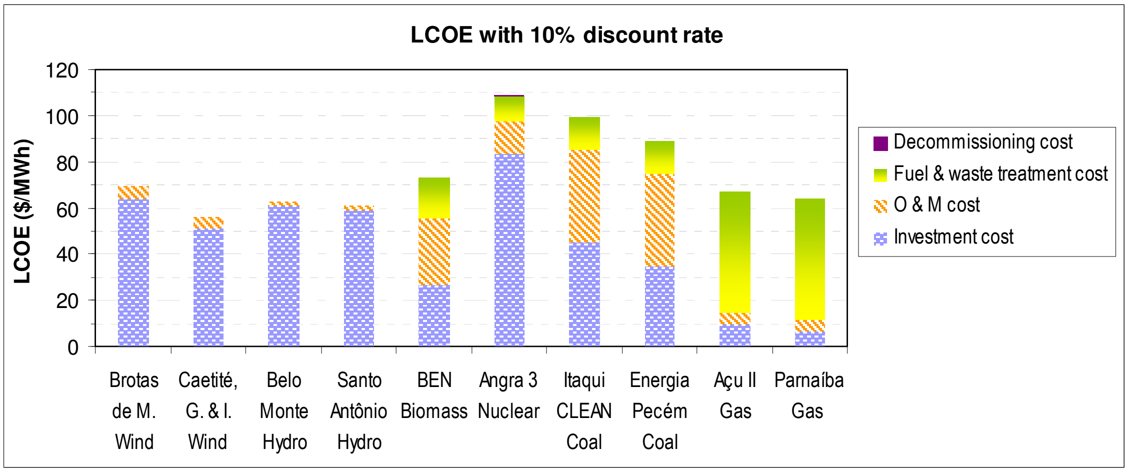


Figure 23: LCOE with high discount rate scenario.

Figure 24, shows the LCOE separated by component costs for the Brazilian PV and CSP case studies, and for the international CSP and wave power projects.

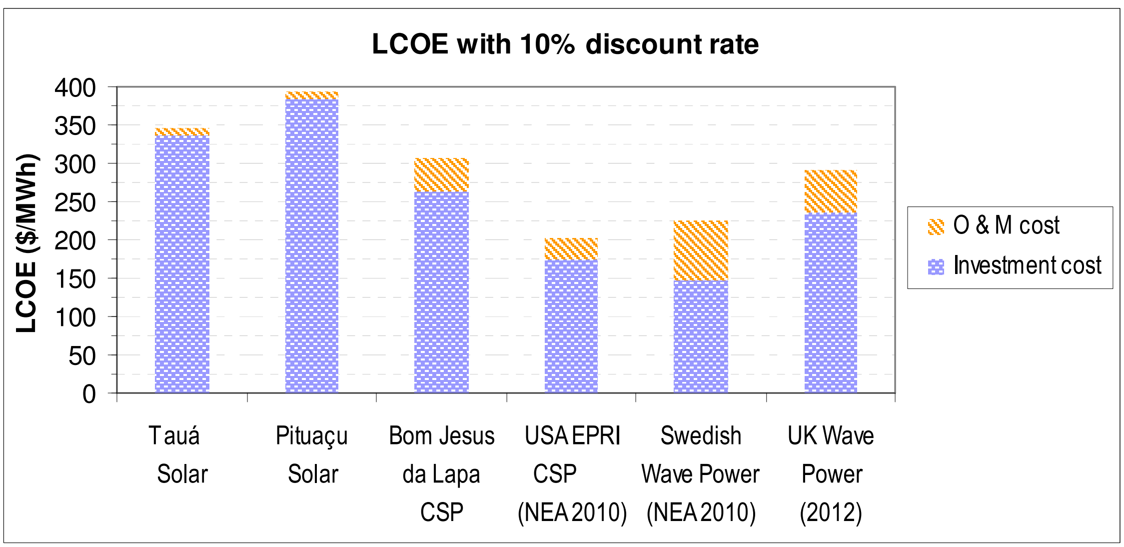


Figure 24: LCOE with high discount rate scenario.

Considering the results using a 10% discount rate without the influence of carbon taxes, the LCOE analysis shows that the cheapest project of all the case studies analysed was the Caetité, Guanambi and Igaporã wind farm complex, with a LCOE of $56.10/MWh. Then the next cheapest technology in Brazil is hydroelectricity – the Santo Antônio Hydro plant was slightly cheaper of the two hydroelectric case studies with a LCOE of approximately $61.14/MWh. Belo Monte Hydro was only marginally cheaper than the fossil fuel gas turbine projects, the cheapest being the Parnaíba gas plant with a LCOE of $63.89/MWh. The Açu II gas plant and Brotas de Macaúbas Wind Farm (considering that currently this project receives a carbon credit of $2.13/MWh) had similar LCOE results at $66.88/MWh and $67.60/MWh respectively. Despite the fact that Brotas de Macaúbas benefits from carbon credits it was still more expensive than the other wind farm case study due to a lower capacity factor and a more expensive overnight cost per MW of installed capacity. However both the coal power stations were more expensive with LCOE results of $88.76/MWh for the Pecém plant and $98.99/MWh for the Itaqui "Clean" Coal power station. The later coal power station was more expensive due to the 30% increase in capital costs for the carbon capture and sequestration (CCS) equipment. Of all the traditional technologies, the nuclear plant was by far the least competitive with a LCOE of $109/MWh. This result is due to the large capital cost and the long lead construction time of the nuclear reactor.

9.4. High discount rate scenario with carbon credits and taxes

Table 4 shows the LCOE for all the case studies using a real discount rate of 10%, with and without the influence of carbon credits and taxes. The calculation method used is the same as with the low discount rate analysis. That is, the total LCOE is first calculated to reflect the current situation in Brazil. Then the impact of carbon credits and carbon taxes is taken into consideration for each of the different case studies. The LCOE totals for all the case studies, considering carbon prices of $100, $200 and $300 per ton of CO_{2eq}, are shown in the last 3 lines of table 4. Figure 25, shows the LCOE graphically using a 10% discount rate, with a carbon price increasing from $0 - $300/t$CO_{2eq}$.

The gross profit margins for some of the case study projects are shown in table 4. It should be noted that only the wind power projects were profitable when using the 10% discount rate. The hydroelectric projects had the worst profit margins with Belo Monte recording a loss of 38%, and the Angra 3 nuclear reactor was not much better with a loss margin of 32.5%.

Table 4: LCOE for all the case studies, using a real discount rate of 10%, with and without the influence of carbon credits and taxes.

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	60.80	58.91	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	2.20	2.23	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	$/MWh	-2.13		-	-	-	-	-	-	-	-	-	-	-	-		-
TOTAL LCOE (current situation in Brazil)	**$/MWh**	**67.60**	**56.10**	**63.01**	**61.14**	**72.94**	**109.01**	**98.99**	**88.76**	**66.88**	**63.89**	**344.56**	**392.48**	**307.55**	**202.45**	**224.15**	**292.03**
Gross Profit Margin (Elec.price-LCOE)	$/MWh	1.21	16.15	-23.91	-22.53		-35.43			-5.00	-2.01						
Gross Profit Margin (percentage)	**%**	**1.8%**	**28.8%**	**-38.0%**	**-36.8%**		**-32.5%**			**-7.47%**	**-3.14%**						
Carbon credit / tax at $100/ton of CO2eq	$/MWh	-20.55	0.00	28.65	0.00	-20.55	0.00	10.01	100.10	46.90	46.90	-20.55	0.00	-20.55	-20.55	-20.55	-20.55
LCOE with Carbon price of $100/tCO2eq	**$/MWh**	**49.18**	**56.10**	**91.66**	**61.14**	**52.39**	**109.01**	**109.00**	**188.86**	**113.78**	**110.79**	**324.01**	**392.48**	**287.00**	**181.90**	**203.60**	**271.48**
LCOE with Carbon price of $200/tCO2eq	**$/MWh**	**28.63**	**56.10**	**120.32**	**61.14**	**31.84**	**109.01**	**119.01**	**288.96**	**160.68**	**157.69**	**303.46**	**392.48**	**266.45**	**161.35**	**183.05**	**250.93**
LCOE with Carbon price of $300/tCO2eq	**$/MWh**	**8.08**	**56.10**	**148.97**	**61.14**	**11.29**	**109.01**	**129.02**	**389.06**	**207.58**	**204.59**	**282.91**	**392.48**	**245.90**	**140.80**	**162.50**	**230.38**

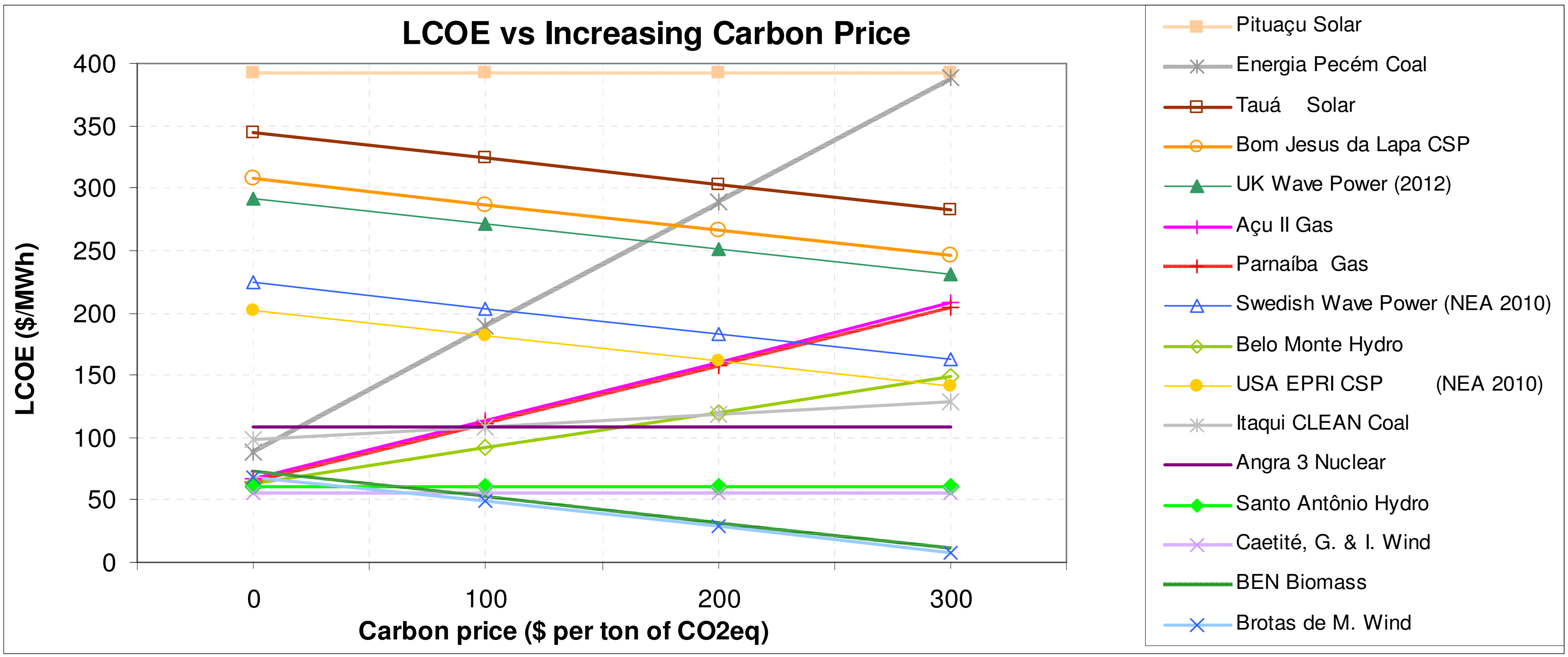


Figure 25: LCOE shown graphically at a 10% discount rate with a carbon price increasing from $0 - $300/t$CO_{2eq}$.

Considering the results with carbon taxes and a 10% discount rate, the LCOE varies depending on the technology and depending on the level of carbon tax. This is best illustrated in the graph shown above in figure 25. Above about $15 per ton of CO_{2eq} the Itaqui “Clean” Coal power station begins to be more competitive than the Pecém coal plant without CCS technology, but is still not more competitive than the gas plants until the carbon price is above $100 per ton of CO_{2eq}. Also at about $100 per ton of CO_{2eq} the gas technologies become less competitive than the nuclear power station.

Assuming that the Belo Monte plant would be subject to carbon taxes due to the impact caused by methane emissions from its reservoirs, above a carbon price of $25 per ton of CO_{2eq}, Belo Monte becomes more expensive than the biomass plant and the Brotas de Macaúbas wind farm. At that same carbon price Belo Monte is already uncompetitive compared to the cleaner hydroelectricity plant of Santo Antonio and the cheaper wind farm complex.

The Brazilian solar PV and CSP case studies all have a LCOE above $300/MWh using the 10% discount rate. As there are almost no forms of subsidies existing in Brazil, these projects are not currently economically viable compared to the other energy sources analysed. The solar energy and wave energy technologies could also be eligible to receive carbon credits under the CDM. However, even if approved, for a carbon price of $100 per ton of CO_{2eq}, the LCOE would only drop by about $20.55/MWh in each case. This is not nearly enough to make them competitive. Only with a carbon price above $175 per ton of CO_{2eq} (as per the IEA (2010) BLUE Map scenario), would the Brazilian solar PV and CSP case studies begin to be competitive with the Pecém coal plant (which is the most expensive of the viable technologies, due to the high proportion of carbon taxes that would be incurred with such a high carbon price).

10. SENSITIVITY ANALYSIS

In this section the sensitivity of the LCOE to changes in the discount rate, inflation, operational costs and capacity factor is analysed. The LCOE of different generation technologies are affected in different ways.

10.1. Impact of real discount rate, inflation and operational costs

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.

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 operations and maintenance 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 operations and maintenance. 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 compared to other generation technologies. On the other hand, if the price of gas drops then the LCOE for gas power plants would drop proportionally. For example the LCOE analysis above assumed a gas turbine efficiency of 48% and used a fixed gas price (including transportation) of $52.37/MWh taken from the NEA-IEA-OECD report (2010). However, using Petrobras (2012) as a source for the "city gate" gas price and assuming there are no other intermediaries or transport costs, results in a natural gas price of $30.43/MWh (assuming the same gas turbine efficiency). Therefore, with a 5% discount rate, the overall LCOE for the Parnaíba gas fired power plant would drop to \$39.20/MWh making it competitive with wind power. This example demonstrates the sensitivity that a LCOE analysis has to fuel price variations, and also shows that it is important to use the same source where possible for various types of fuel price data and to include fuel transport costs.

Similarly, if operations and maintenance 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 as shown in sections 9.2 and 9.4. 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 the running cost to produce electricity from these plants rises 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.

10.2. Impacts of changes in operational capacity factor

LCOE calculations are also very sensitive to changes in the capacity factor of a particular generation technology. The capacity factor is another input to the equation which can significantly change the final LCOE result. This is particularly so for those generation technologies that have large upfront costs and low or no fuel costs and assuming that the annual operations and maintenance costs don't vary even if the capacity factor changes. If for example, the capacity factor is reduce by a factor of 20% (that is, the total energy generated per year is only 80% of that forecast) the LCOE for wind, hydro, and solar technologies increases by approximately 25%. This can be seen in table 5, where the LCOE with a 5% discount rate is shown for these exact circumstances. The calculations in table 5 assume that the annual operations and maintenance costs for all the case studies remains approximately the same regardless of the reduction of 20% in annual energy output. Thus, the operations and maintenance cost per MWh actually increases 25%.

However gas power plants are far less susceptible to poor capacity factor performance, as the majority component of the LCOE is the fuel consumption cost. If the capacity factor is reduced by a factor of 20% and 20% less energy is produced, then 20% less fuel is consumed and the cost of fuel per MWh remains unchanged. Thus, as can be seen in table 5, under the new capacity factor circumstances, the gas power plants become more competitive than the nuclear and biomass plants.

In general, the LCOE of renewable technologies are most sensitive to a reduced capacity factor and the resulting reduction in annual energy output, but biomass, coal fired and particularly nuclear power plants are still very susceptible to poor capacity factor performance. For example, the Angra I nuclear reactor which commenced commercial operation in 1985 has, to date, only achieved a cumulative capacity (load) factor of 48% due to steam supply system problems and continual outages (PRIS, 2013). During the first 25 years of operation the capacity factor and energy supplied to the grid was approximately half of what was initially expected. Thus the LCOE for Angra I was almost double expectations. Only in 2011 and 2012 did it finally achieve a capacity load factor greater than 80%. The Angra II reactor which commenced commercial operation in 2001 has performed substantially better with a cumulative capacity (load) factor of 81%; however construction of this reactor began in 1976. The long lead time of 25 years before commercial operations, means the LCOE for Angra II has been hugely inflated above initial expectations.

Another interesting effect of a reduced (or increased) capacity factor is that the CO_{2eq} produced by the Belo Monte hydroelectric reservoirs remains the same even if the annual energy production is reduced (or increased). If, for example, the expected capacity factor is not achieved due to a water shortage and only 80% of the nominal annual energy is produced, the CO_{2eq} per MWh emitted actually increases by 25% and thus the associated carbon taxes per MWh (if applied) also increase by 25%. This becomes significant when analysing the LCOE with the carbon tax component included in the total, as can be seen graphically in figure 26.

Table 5: LCOE for all the Brazilian case studies using a real discount rate of 5%, with the capacity factors reduced by a factor of 20%. Carbon credits and taxes are also shown.

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
Capacity Factor reduced by 20%	%	**32%**	**37%**	**32%**	**56%**	*68%*	**65%**	***68%***	**68%**	***64%***	***64%***	**14%**	**14%**	***16%***
Investment cost	$/MWh	47.04	37.67	31.78	31.47	19.8	44.99	28.03	21.70	6.55	4.86	258.04	293.92	202.82
O & M cost	$/MWh	7.70	6.17	2.75	2.79	35.66	17.60	42.91	42.91	6.12	6.12	9.92	11.30	52.94
Fuel & waste treatment cost	$/MWh	-	-	-	-	17.33	10.55	13.94	13.94	52.35	52.35	-	-	-
Decommissioning cost	$/MWh	-	-	-	-	-	0.95	-	-	-	-	-	-	-
Actual carbon credit at $10.38/tCO2eq	$/MWh	-2.13		-	-	-	-	-	-	-	-	-	-	-
TOTAL LCOE (current situation in Brazil)	**$/MWh**	**52.62**	**43.84**	**34.53**	**34.26**	**72.80**	**74.09**	**84.88**	**78.55**	**65.02**	**63.33**	**267.96**	**305.22**	**255.76**
Gross Profit Margin (Elec.price-LCOE)	$/MWh	16.20	28.41	4.56	4.36		-0.50			-3.14	-1.45			
Gross Profit Margin (percentage)	**%**	**30.8%**	**64.8%**	**13.2%**	**12.7%**		**-0.7%**			**-4.83%**	**-2.29%**			
Carbon credit / tax at $100/ton of CO2eq	$/MWh	-20.55	0.00	35.82	0.00	-20.55	0.00	10.01	100.10	46.90	46.90	-20.55	0.00	-20.55
LCOE with Carbon price of $100/tCO2eq	**$/MWh**	**34.20**	**43.84**	**70.35**	**34.26**	**52.25**	**74.09**	**94.89**	**178.65**	**111.92**	**110.23**	**247.41**	**305.22**	**235.21**
LCOE with Carbon price of $200/tCO2eq	**$/MWh**	**13.65**	**43.84**	**106.17**	**34.26**	**31.70**	**74.09**	**104.90**	**278.75**	**158.82**	**157.13**	**226.86**	**305.22**	**214.66**
LCOE with Carbon price of $300/tCO2eq	**$/MWh**	**-6.90**	**43.84**	**141.98**	**34.26**	**11.15**	**74.09**	**114.91**	**378.85**	**205.72**	**204.03**	**206.31**	**305.22**	**194.11**

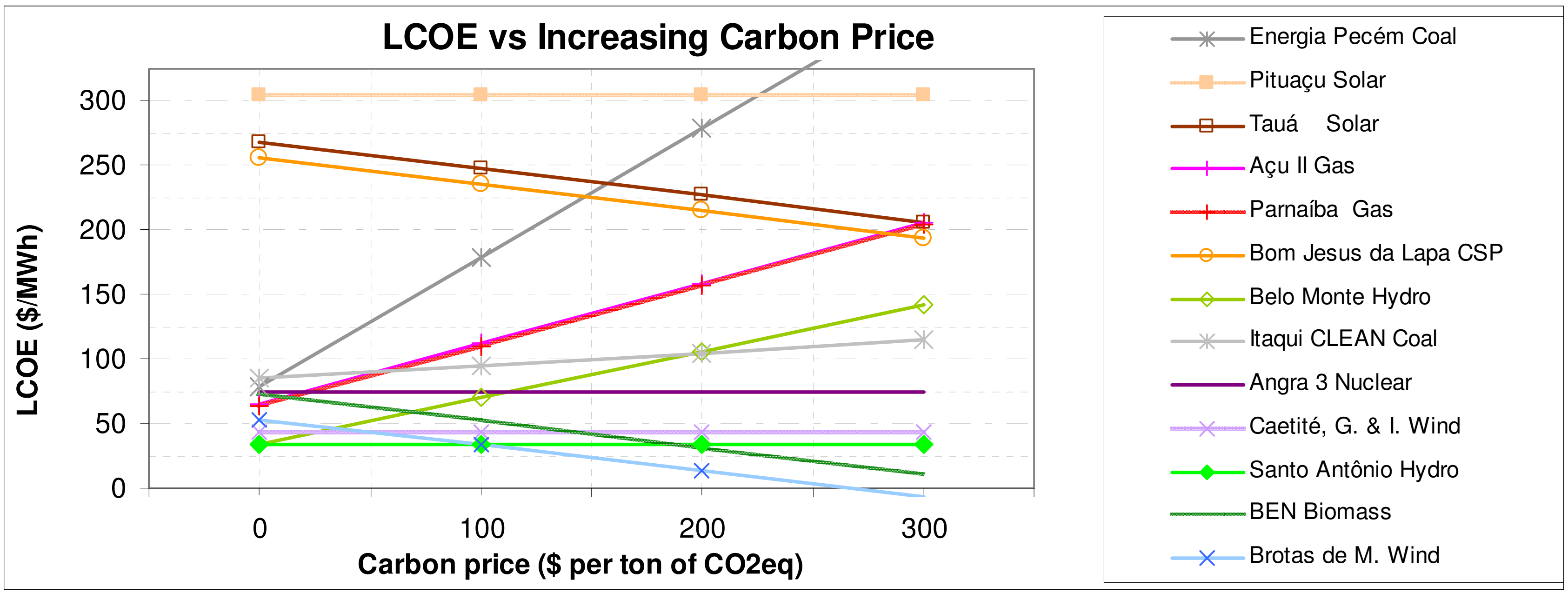


Figure 26: LCOE with a 5% discount rate, with capacity factors reduced by a factor of 20% and with a carbon price increasing from $0 - $300/t$CO_{2eq}$.

11. LCOE IN BRAZIL COMPARED TO AUSTRALIA

In order to compare the LCOE in Brazil to some generation technologies in Australia, a number of Australian projects and studies were examined. An exchange rate of US$1 = Au$1.00 (from May 2013) was used to convert Australian dollars to US dollars. The Infigen Woodlawn wind farm in NSW Australia was used as case study. It is a 48MW wind farm completed in 2011 with a capacity factor of 39% and which had a total investment of $115 million (INFIGEN ENERGY, 2012 and DAVID CLARKE, 2012). The second case study was the Kogan Creek Concentrated Solar Thermal (CSP) Boost project which will use Compact Linear Fresnel Reflectors to provide solar thermal energy to heat feedwater into superheated steam, supplementing the existing coal fired boiler at the Kogan Creek Power Station. The concentrated solar thermal system will produce a maximum of 44 MW of additional electricity during peak solar conditions, but will only have a capacity factor of 12%. The project, which commenced construction in 2011, has a capital cost of $104.7 million (CS ENERGY, 2012). The LCOE for grid connected utility scale PV was calculated, based on data from the Australia PV Association (APVA, 2012).

The LCOE for other generation technologies in Australia including a 50MW wave power plant (already mentioned in section 9.1) as well as geothermal, coal and gas power were estimated in the NEA IEA OECD (2010) report based on information provided by the Energy Supply Association of Australia. The results for the LCOE in Australia with a 5% discount rate can be seen in figure 27.

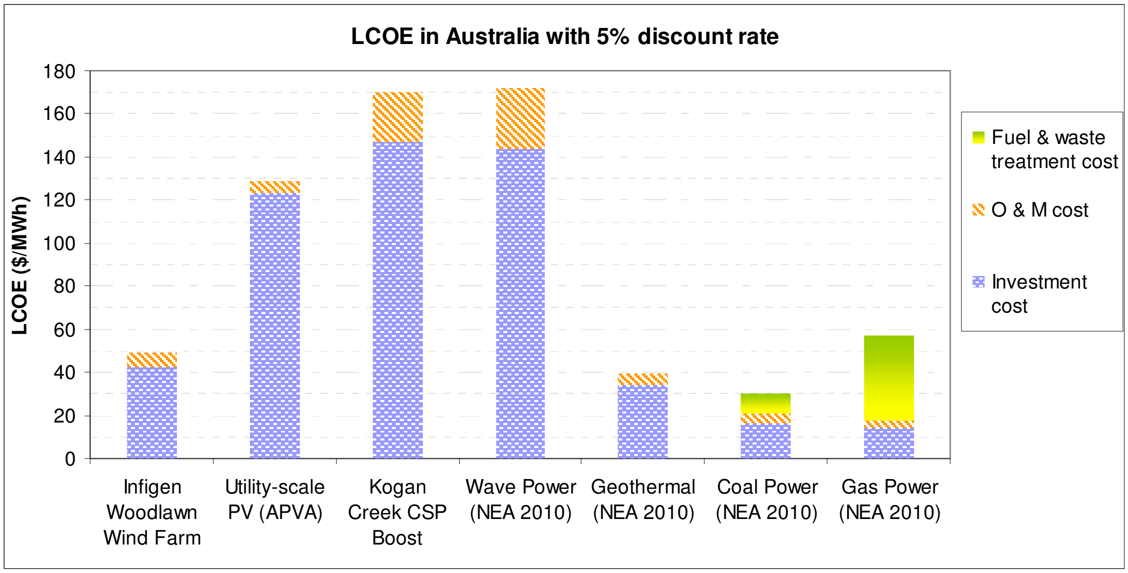


Figure 27: LCOE in Australia shown in US dollars ($) separated by component costs.

The LCOE results for Australia shown in figure 27 can be compared to those for Brazil shown in figures 20 and 21. It can be observed that the LCOE of wind power in Brazil is approximately 25% cheaper than in Australia and less again when compared to some other regions. On the other hand, utility scale PV in Australia is only 50-60% of the cost of large scale PV in Brazil. The LCOE of coal power in Australia is less than half of that in Brazil due to the low operations and maintenance costs and low fuel costs in Australia. Whereas electricity generated from gas power is comparable (with the LCOE from gas power in Australia being only about 6% cheaper than in Brazil).

Concentrated solar power in Australia is at least 15% cheaper than that estimated for Brazil (despite the below average capacity factor of the Kogan Creek Solar Boost project). However, at the Kogan Creek plant there is already an existing steam turbine installed as part of the coal fired power station, so the total investment for the CSP plant is significantly reduced compared to a stand-alone CSP plant.

12. SOCIAL, ENVIRONMENTAL AND TRANSMISSION EXTERNALITIES

This section evaluates the environmental and social impacts of the different generating technologies and estimates these externality costs. Additionally the costs and energy losses of extended transmission systems are calculated.

12.1. 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 (FEARNSIDE, 2009). 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 slowly decline. Fearnside (2009) 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 (2010) 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. 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.

Several thousand people will have to be relocated as a result of the Belo Monte dam and 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 extraction of large mineral deposits in Pará, including bauxite and the processing of aluminium (FEARNSIDE, 2009). These environmental and social costs will have a significant negative impact in the coming years; however they are not easily measured quantitatively and are generally not included in economic viability calculations or planning decisions. Therefore besides the typical economic indicators of the different generation technologies considered, it is important to also consider the environmental impacts and if possible estimate their financial cost.

12.2. 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 (2005) 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 power 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), (ATSE, 2009) though combined cycle plants perform more efficiently. 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 (ATSE, 2009). 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 emissions factor, these estimates could be reduced by at least 50-75%.

The majority of wind turbines installed in Brazil are manufactured locally, therefore 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 (ATSE, 2009). 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"* (ATSE, 2009).

The impact due to GHG emissions will have global effects, though 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 Europe. Currently the NE region is suffering from one of its worst droughts in decades.

The GHG damage cost for the Belo Monte and Babaquara dams can be easily estimated. Using the ExternE (ATSE, 2009) 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 (2010) 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. As stated earlier in section 7.2, 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, SO_2 and NO_x emissions from the plant smokestack. Using the ExternE (ATSE, 2009) 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 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.

As a result 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. Though, this is a conservative estimate, as it does not account for inflation since 2005.

12.3. Transmission system externality costs

At significant cost, Belo Monte, when completed will partly resolve power shortages in Brazil for a number of years and will also increase energy imported from the North to the NE and Southeast, 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 Antonio 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, Santo Antonio Energia (2012) 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 (2011) 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 Antonio 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 (GARÇON, 2013), which will serve both the Santo Antonio and Jirau hydroelectric plants if one considers that the Santo Antonio 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 Antonio 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 Antonio 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 (TEIXEIRA, 2012 and MME, 2013). Using the Delucchi and Jacobson (2011) 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 the energy it produces will be supplied 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. Therefore 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.

The actual LCOE of both hydroelectric plants including their respective transmission system costs and losses are shown in tables 6 and 7 and figures 28 and 29, which detail the overall LCOE for all the case studies including their respective externality costs.

Table 6: 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

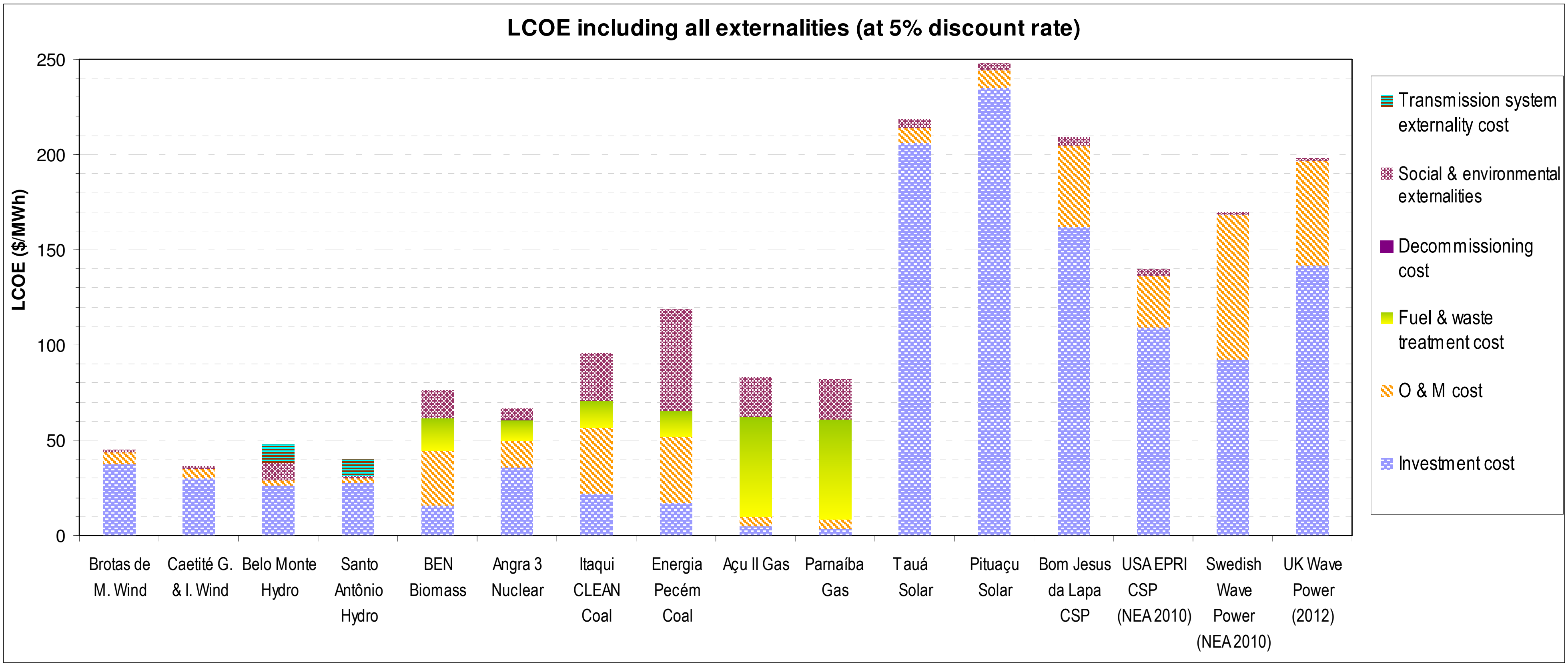


Figure 28: LCOE shown graphically at a 5% discount rate with social, environmental and transmission system externality costs.

Table 7: 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

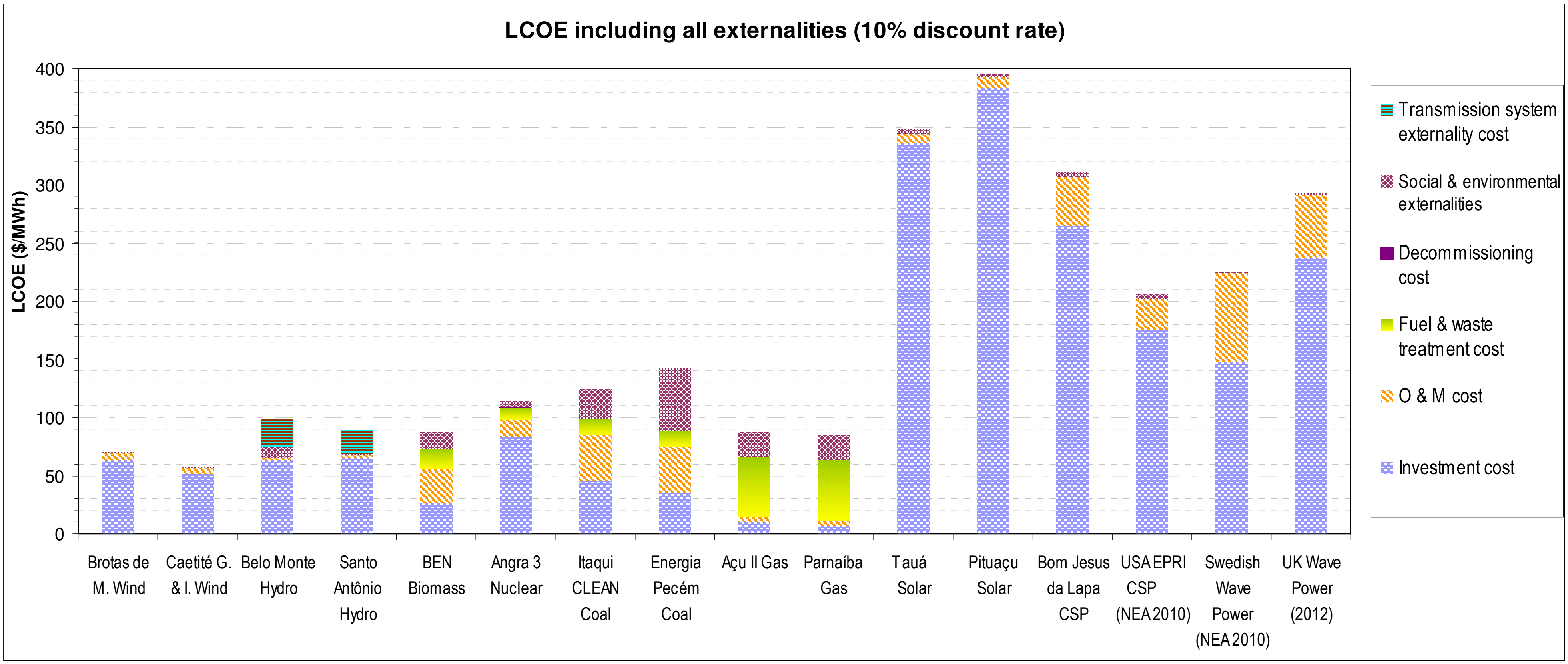


Figure 29: LCOE shown graphically at a 10% discount rate with social, environmental and transmission system externality costs.

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 Antonio. 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 Antonio and Belo Monte hydroelectric plants respectively and also significantly more competitive than all the other case studies analysed.

Besides new hydroelectric plants in the Amazon and new fossil fuel plants which both have very large externality costs, new wind farms in the Northeast, like Brotas de Macaúbas, are also being constructed and several more have been approved. Fortunately, due to the strong winds 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 (DE JONG et al, 2012). The complementarity of wind power and solar energy with the existing hydroelectric infrastructure (see section 13 for details) helps diversify electricity generation and improves energy security in Brazil (DE JONG et al, 2013). This combined with the minimal environmental impact are big added values for both wind and solar technologies that cannot easily be given a financial value.

13. RENEWABLE ENERGY OUTPUT IN RELATION TO THE ELECTRICITY LOAD CURVE AND HYDROELECTRICITY IN THE NORTHEAST REGION

13.1. Variation of solar resources in the region during a typical year

The NE region is located between the Equator and the Tropic of Capricorn, and receives the highest annual average solar radiation in the country (see figure 30) which is due to the low precipitation rate. This enormous potential for electricity generation remains largely unexplored, with the exception of a few small photovoltaic systems in some isolated rural communities and the recently completed 1 MW Solar PV Plant in Tauá, Ceará, which is connected to the grid (MPX LTD., 2011).

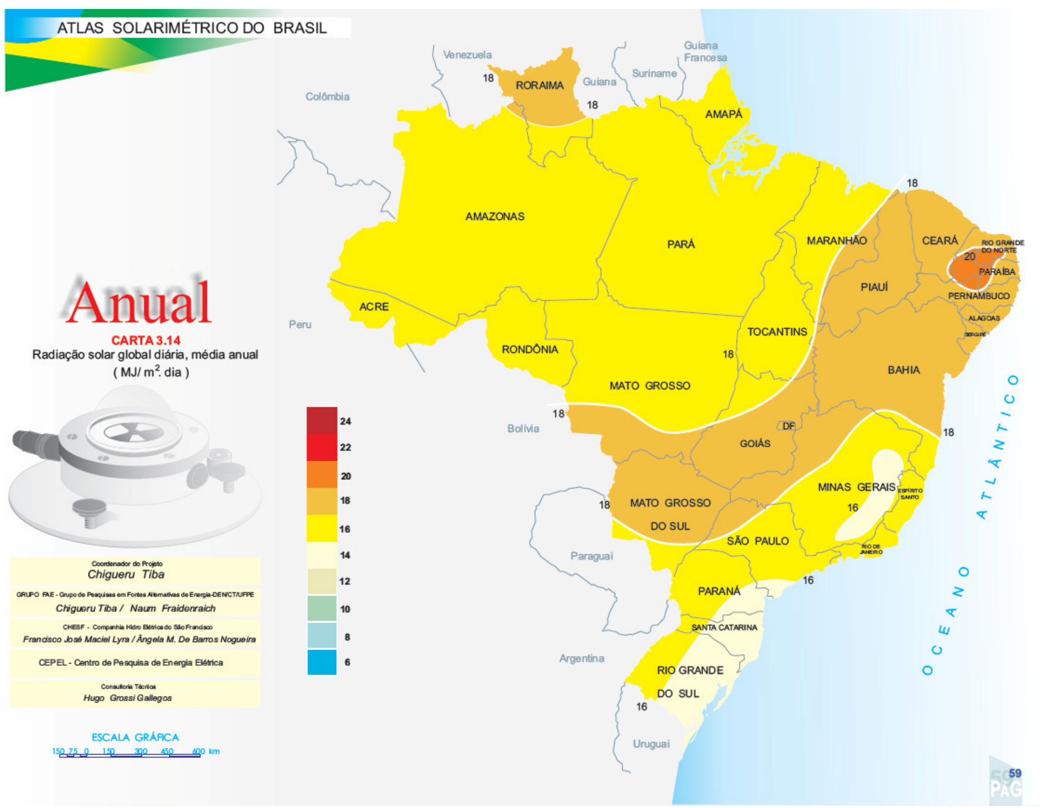


Figure 30: Isolines for annual average daily global solar radiation (horizontal plane). Source: Tiba et al (2001).

The bar graph in Figure 31, which shows the monthly variations of average daily solar radiation (on a horizontal plane) in the MRS during 12 months, is largely representative for most of the Northeast region as is demonstrated by the isolines in Figure 30. There are relatively high values of solar energy even during the winter minimum month of June and the deviation does not exceed 28% from the annual average of 5.25kWh/m^2 (or 18.91 MJ/m^2).

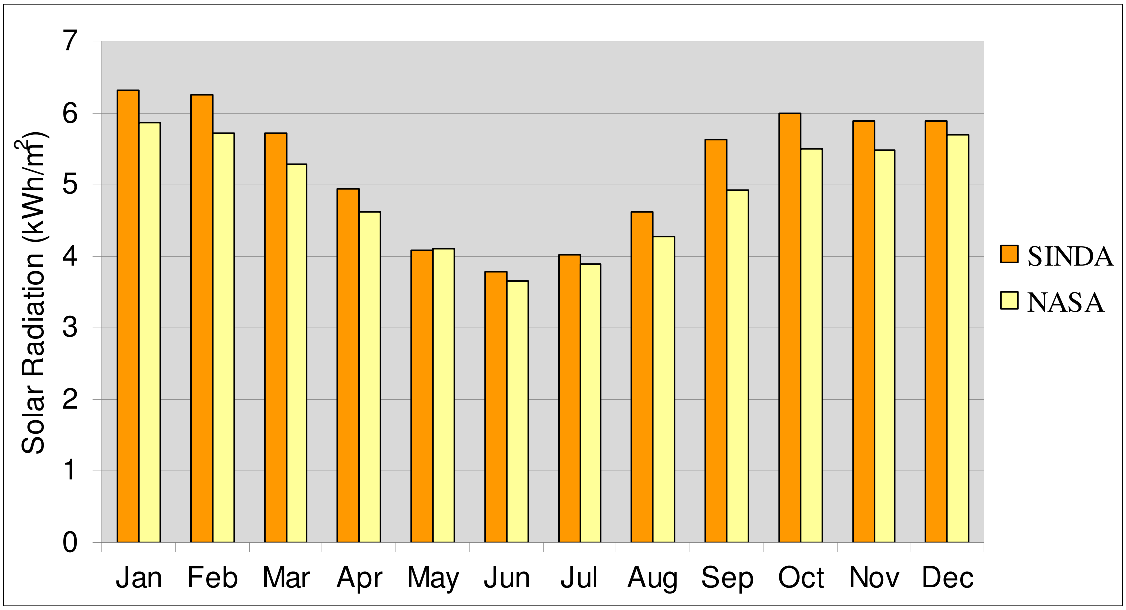


Figure 31: Variation of annual average daily solar radiation (on a horizontal plane) for each month from 1998 to 2009 in the MRS. Sources: INPE (2012) and RETScreen (2012).

13.2. Variation of wind resources in the region during a typical year

As well as the Northeast having the largest solar energy availability in the country (as seen above in figure 30), the Northeast region is also by far the most privileged in terms of wind power potential (see figures 4 and 32). According to the Empresa de Pesquisa Energetica EPE (Energy Research Company) the NE region has the potential to generate 75,000 MW of electric power from wind sources. If only 10% of this wind power potential was implemented, this would easily account for the electricity deficit in the NE that currently is imported from other regions. The best winds occur along the coastal areas of the states of Ceará and Rio Grande do Norte and in the interior of the state of Bahia (in the Chapada Diamantina region). In recent years, particularly in these three areas of the NE region, wind power production has taken off. As of April 2013, wind power makes up 32% and 42% of the total installed generation capacity in the states of Ceará and Rio Grande do Norte respectively (ANEEL, 2013). Figures 34 and 35 show the average wind power generated per month during 2012 in Ceará and Rio Grande do Norte where several wind farms already exist. In 2012 wind energy accounted for 3% of the total electricity generated in the NE (ONS, 2013) and this percentage is expected to grow as new wind farms in the region are commissioned.

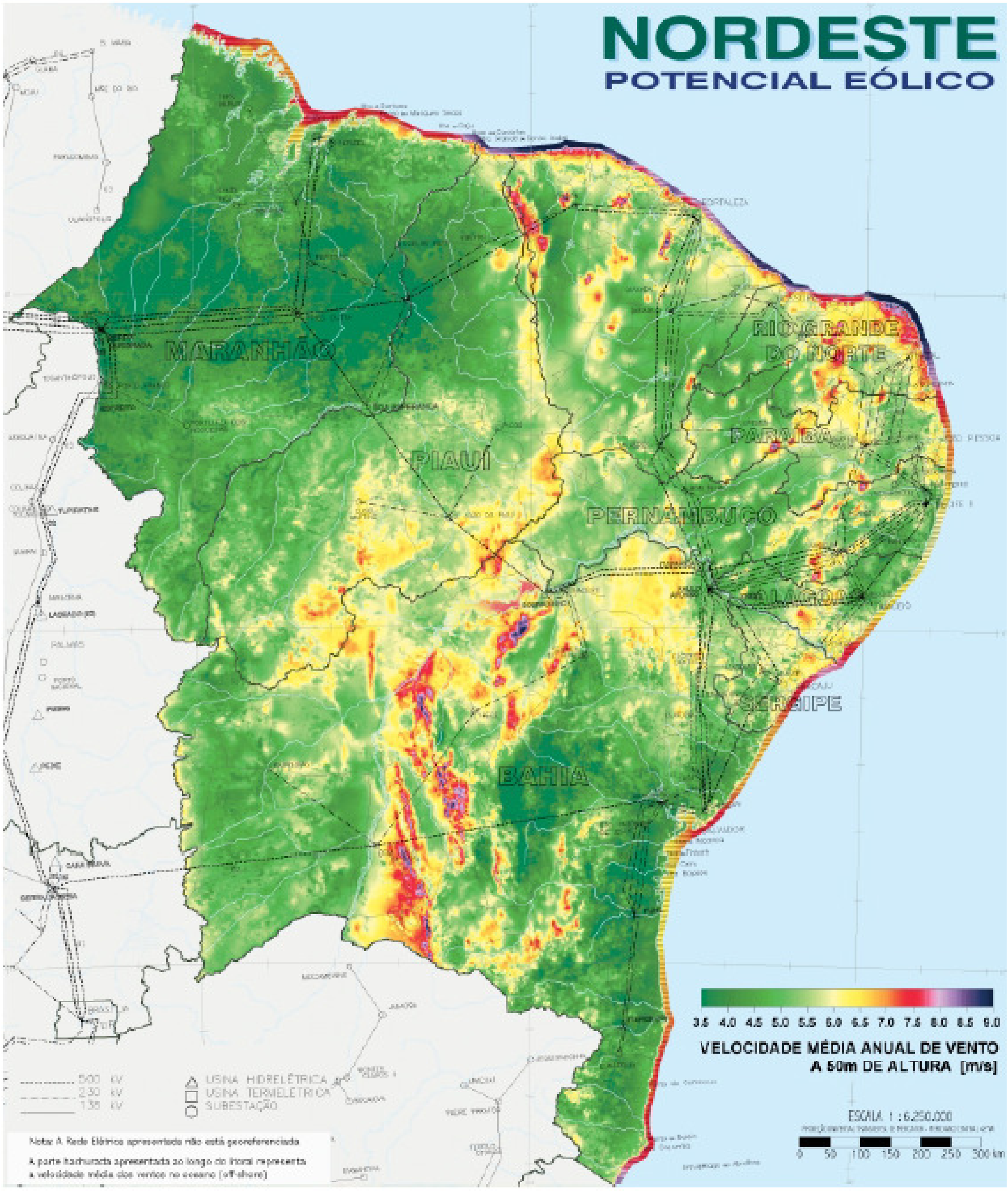


Figure 32: Map of available wind power for the NE region. Source: Amarante et al (2001).

The monthly average wind speed for the MRS over a 12 month period, at a height of 10m, is shown in figure 33. The average wind speed ranges from a maximum in August to a minimum in March. The curve shows little variability, with a maximum deviation of 19.5% around the mean value for the year of 4.5 m/s. Wind speed increases with height in accordance with equation 1 and it can be observed that for the same location, at a height of 80m (the typical height of modern commercial wind turbines) the average annual wind speed would be approximately 7m/s, according to equation 1 and the "Atlas do Potencial Eólico da Bahia". By measuring wind speed data at a different height there is only a change in magnitude, but it does not change the average monthly or daily wind profile curve. The other data sources consulted provided similar average wind speed profiles at height of 30m, 50m and 70m.

$$V_2 = V_1 \cdot (H_2/H_1)^{\alpha} \qquad (1)$$

where:

V_1 is the wind speed at the height of the measurement.

V_2 is the estimated new wind speed at a new height.

H_1 and H_2 are the respective heights.

α is the friction index, which is dependent on the location.

(LI et al 2009).

It should be noted that wind regimes in different regions of the NE can vary from one another. Figures 34 and 35 show the annual profile of wind power generation for Ceará and Rio Grande de Norte. Though not identical to the MRS profile, it can be seen that the minimum wind speeds also occurred in March and April.

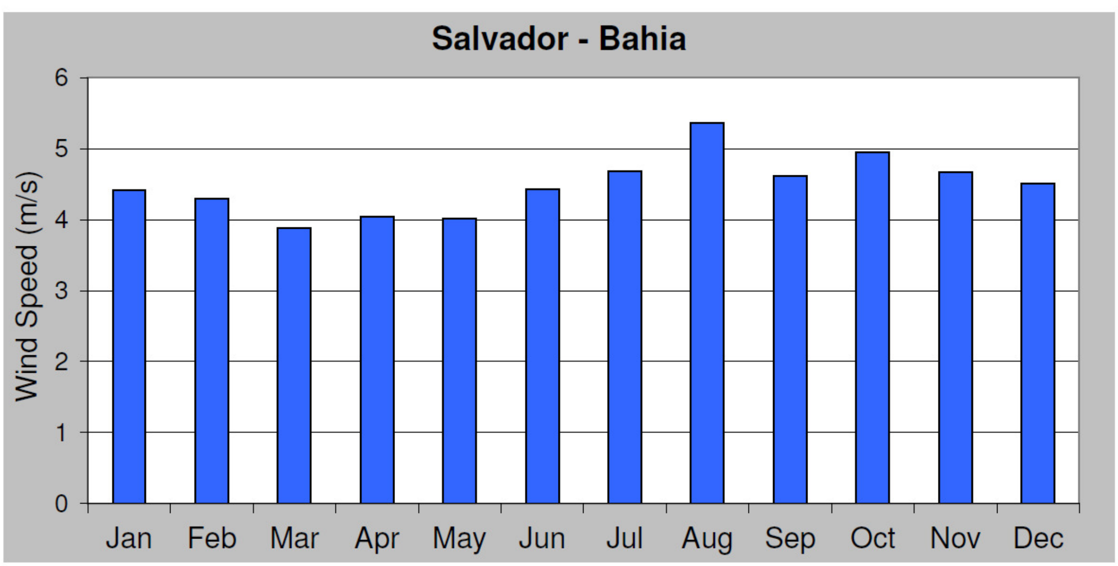


Figure 33: Average wind speed (at a height of 10m) for each month of 2001 in Salvador (NE State of Bahia). Source: Millennium (2002).

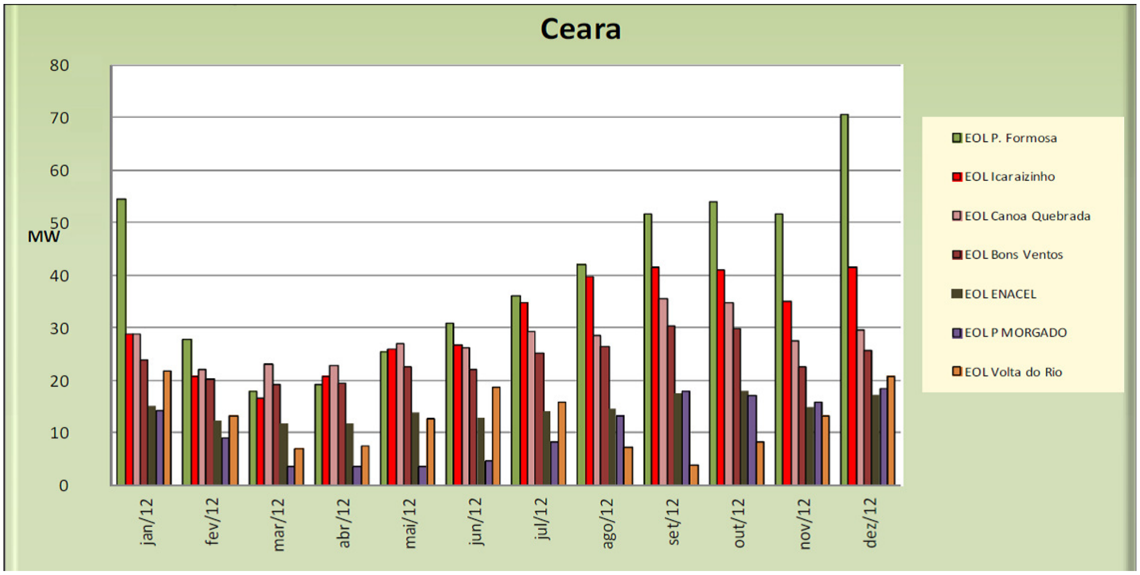


Figure 34: Average power generated by wind farms in the NE State of Ceará (Jan 2012 to Dec 2012). Source: ONS (2012a).

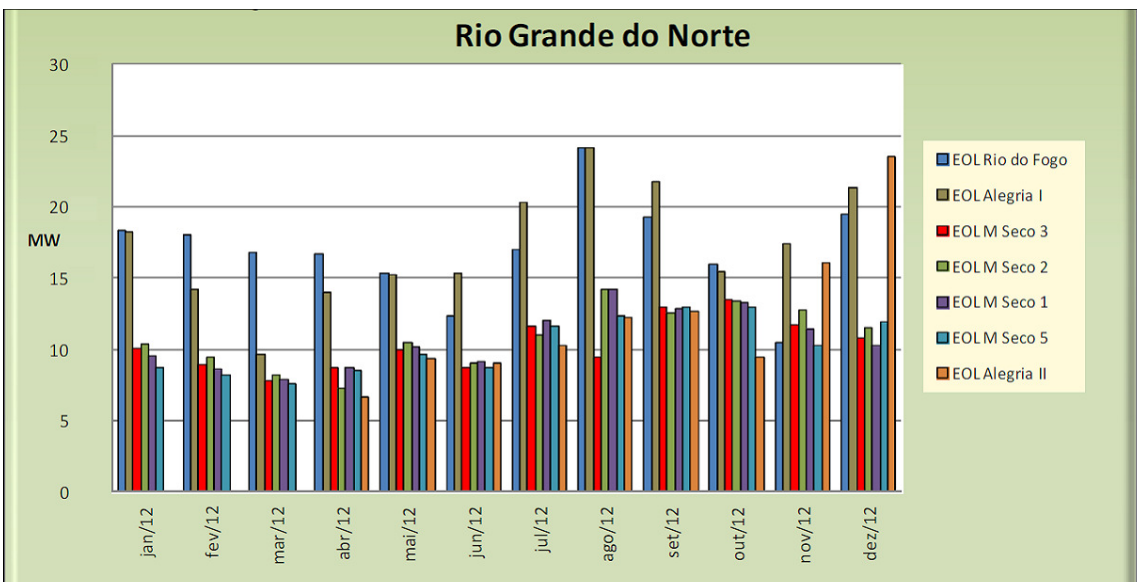


Figure 35: Average power generated by wind farms in the NE State of Rio Grande do Norte (Jan 2012 to Dec 2012). Source: ONS (2012a).

13.3. Variation of hydropower availability in the region during a typical year

The interior of Brazil's Northeast region is known as the Drought Polygon. With 950,000 km^2, it is an irregular shaped region where people live under the recurring threat of water scarcity (the most recent drought occurring in 2012). The semi-arid regions of NE receive an average of less than 800 millimetres of rain annually, most of which falls in a period of three to five months of the year (Dec-Apr). Occasionally there is much less rainfall than the average in consecutive years, which results in long periods of drought. This phenomenon is not anthropogenic, with the worst droughts recorded in 1777-78, 1877-79 and 1915 (ALVES, 1982). However, as already mentioned regional changes in rainfall patterns due to Global Warming may threaten rainfall levels and the production of hydroelectricity to an even larger degree.

Figure 36 shows curves of the monthly variation of the volume of water in the Northeast region's main reservoirs. Based on measurements over the last 13 years the mean curve for the volume of water in the NE reservoirs was calculated and is shown in Figure 37. In Figure 36 it is easy to visualize the drought of 2001, which caused interruptions and outages to the electricity supply in the region and also nationally, due to the reliance on hydroelectric generation.

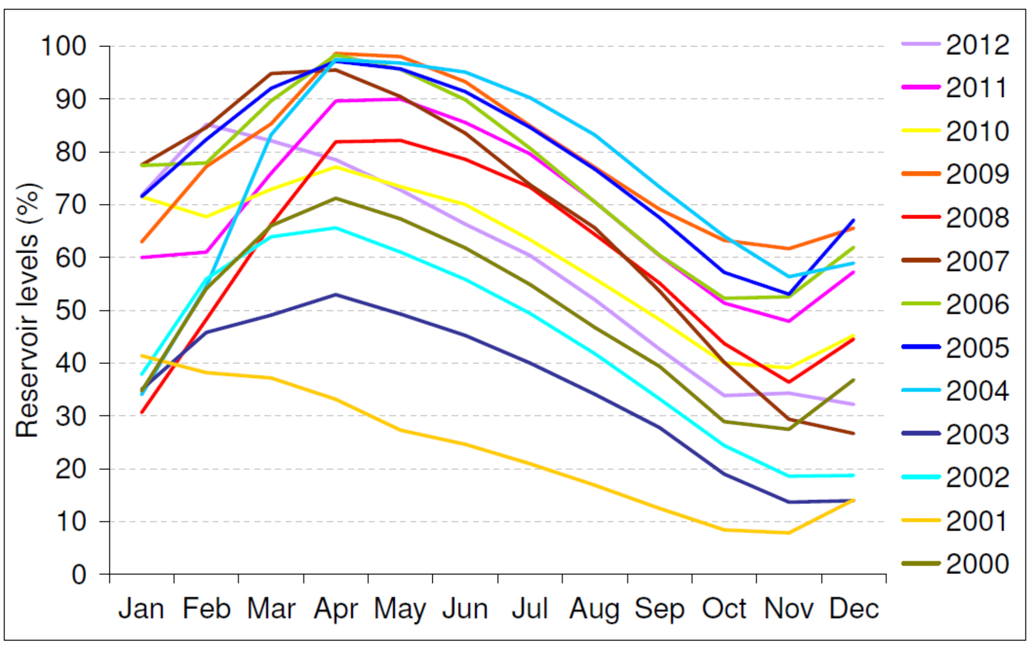


Figure 36: NE reservoir volumes (as a percentage of the total capacity) from 2000 to 2012. Source: ONS (2013).

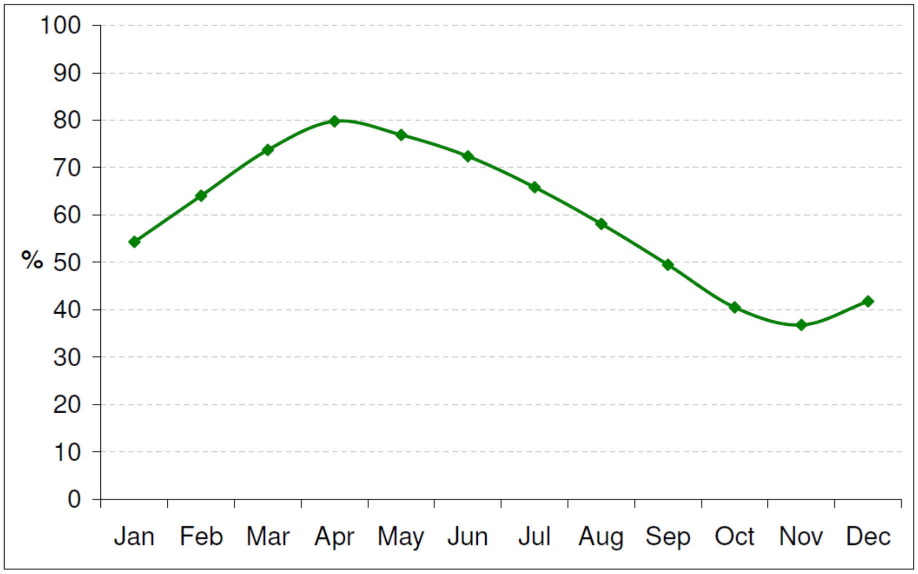


Figure 37: Average reservoir volume level (2000-2012). Source: ONS (2013).

An extension of the drought that began in 1998 caused by the "El Niño" phenomenon, the drought of 2001 was particularly severe compared to earlier ones: at the time, not only the Northeast, but the whole of Brazil was in an energy crisis scenario, which was caused by lack of investments in the energy sector and the lack of rain. This was unprecedented in the country's history.

The government, caught by surprise, was forced to urgently cut 20% of electricity consumption in almost the entire country. After the drought broke in 2002, the application of these cuts - that caused severe losses in the Brazilian economy - was eased thanks to the positive results of a voluntary electricity-rationing campaign. One of the consequences of this crisis was the impetus given to electricity generation from fossil fuels in the following years.

Research on an even longer time frame can be done on the hydroelectric resources of the NE region, by also focusing on the monthly variations of the São Francisco River's water flow, as the ONS has flow data for the past 80 years. To calculate the Pearson correlation coefficients, the river's mean flow rate for each month of a calendar year was considered as shown in figure 38.

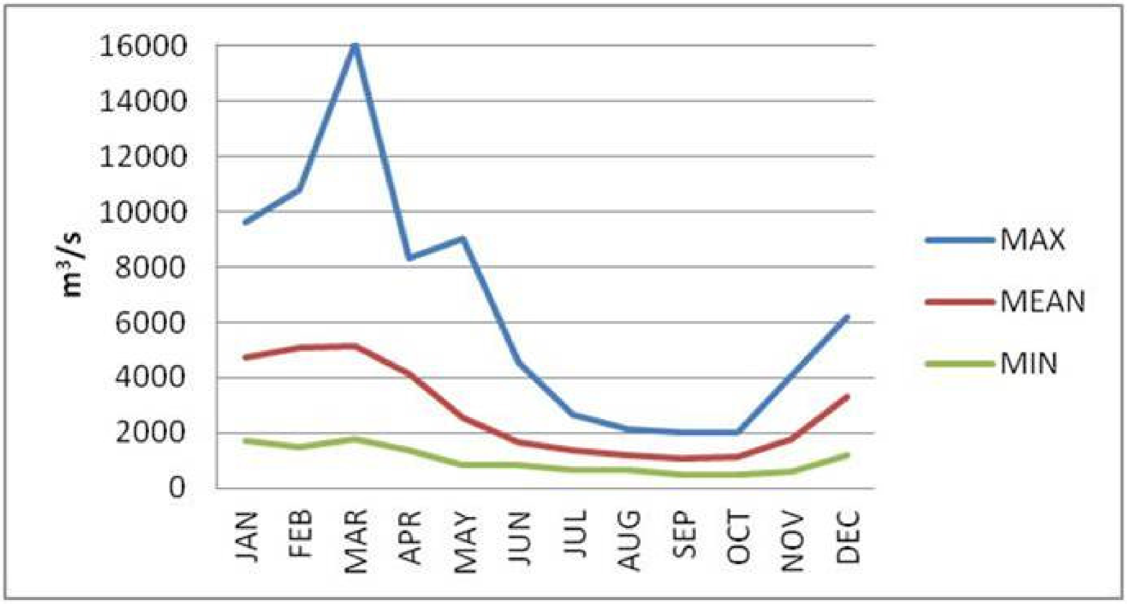


Figure 38: Flow rate of the São Francisco River: curves with the maximum, mean and minimum recorded flow for each month. Average values from 1931 to 2010. Source: ONS (2011c).

13.4. Variation of the NE's electricity demand (load curve) during a typical year

In 2011 the average electricity demand in the NE region was approximately 8,500 MW with instantaneous peaks of 10,000 MW (ONS, 2012b). The three major metropolitan areas in the NE (Salvador, Recife and Fortaleza) account for an average demand of 2100, 1100 and 1500 MW respectively.

A correlation between energy demand and daily temperatures has been established by many electrical utilities as there is a causal relationship: electrical consumption tends to drop on temperate days due to lower demand for air conditioning (or heating in the case of colder climate countries). According to the ONS, the occurrence of milder temperatures during 2011 was one of the reasons the electricity demand did not rise significantly in the NE region compared with other years (ONS, 2012b). In the NE region there is a large influence on electricity demand from air conditioning use. That is, there is increased electricity demand during the austral summer (from November to March) when the highest temperatures typically occur and there is less electricity demand in the cooler months from May to August.

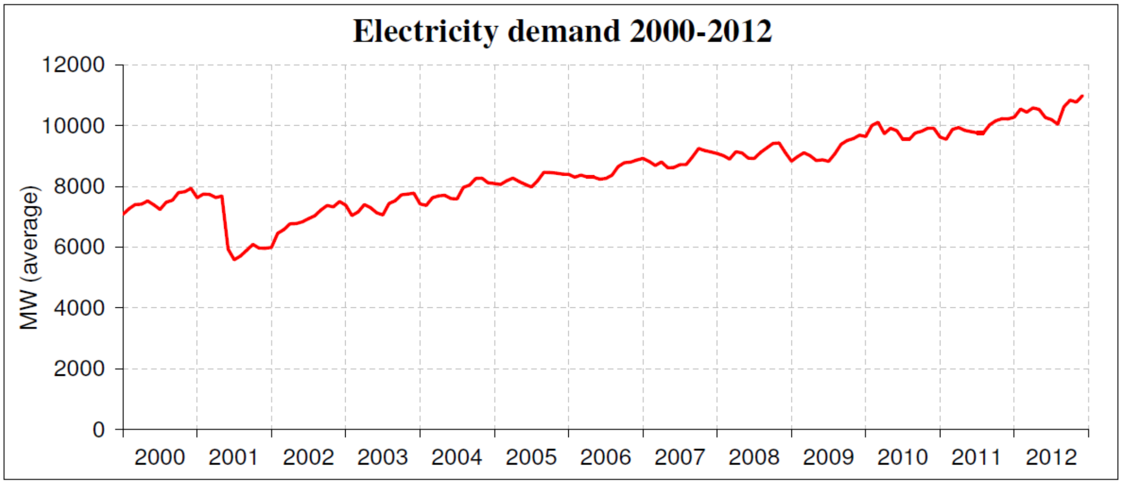


Figure 39: Growth in electricity demand in the NE region since 2000. Source: ONS (2013).

The resulting Load Profile for the NE region, considering data from the last 13 years (as shown in figure 39), is influenced by seasonal consumption patterns as explained above and by the annual growth in demand. As a result demand in the last months of the year tends to be higher than in the initial months of the same year. Therefore the annual curves are first normalized and then the average of these load profiles is shown in figure 40.

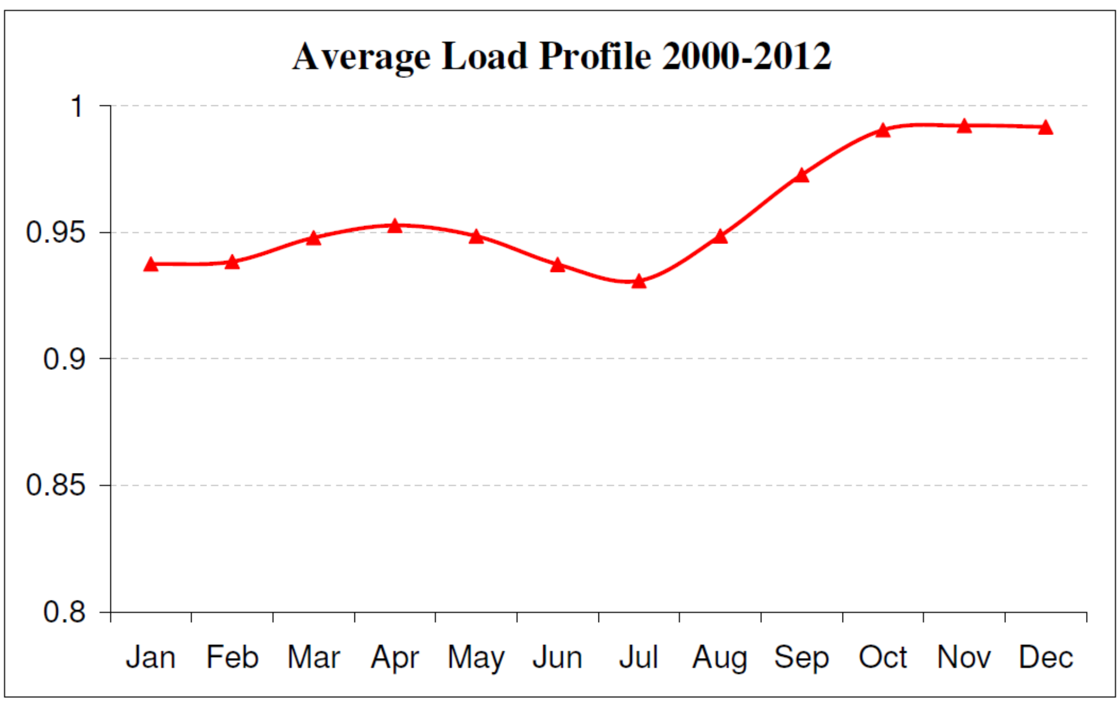


Figure 40: Normalized average electricity load profile in the NE region during the last 13 years. (Vertical scale only shows the upper 20% part or the curve). Data from 2001 and 2002 were disregarded, because they were atypical years due to a severe drought which resulted in electricity-rationing in 2001 and the removal of rationing in 2002. Source: ONS (2013).

13.5. Correlations and results found

The calculated Pearson correlation coefficients are shown in Table 8. There is a significant positive correlation between the individual renewable energy sources (wind and solar) and the yearly load curve. The negative correlation between the renewable energy sources (Wind + Solar combined) and the NE's hydroelectric availability (reservoir volume levels) has a much larger magnitude (0.815). Importantly this demonstrates that during the months when hydroelectric capacity is reduced, the average output from the renewable energy sources (wind and solar) is greater and vice versa.

Table 8: Pearson correlation coefficients for the studied parameters.

	Solar	**Wind**	**Combined Solar + Wind**
Demand (yearly load curve)	0.464	0.286	0.546
Hydro Availability (reservoir levels)	-0.595	-0.611	-0.815
São Francisco River Flow Rate	0.459	-0.703	0.075

Although the values of the coefficients indicate a medium-strong level of correlation between the parameters, the correlations are better illustrated graphically in Figure 41, which shows the variations of all the parameters during a typical year.

Solar radiation has a variation of 40% between its minimum and maximum annual values. For wind, the variation for the studied years was around 27%. These resources complement each other very well: lower wind speeds tend to occur during the austral summer (from November to March) when solar radiation is at its maximum. During austral winter, from May to September, solar radiation is at its lowest levels, while wind speeds tend to be stronger and more consistent.

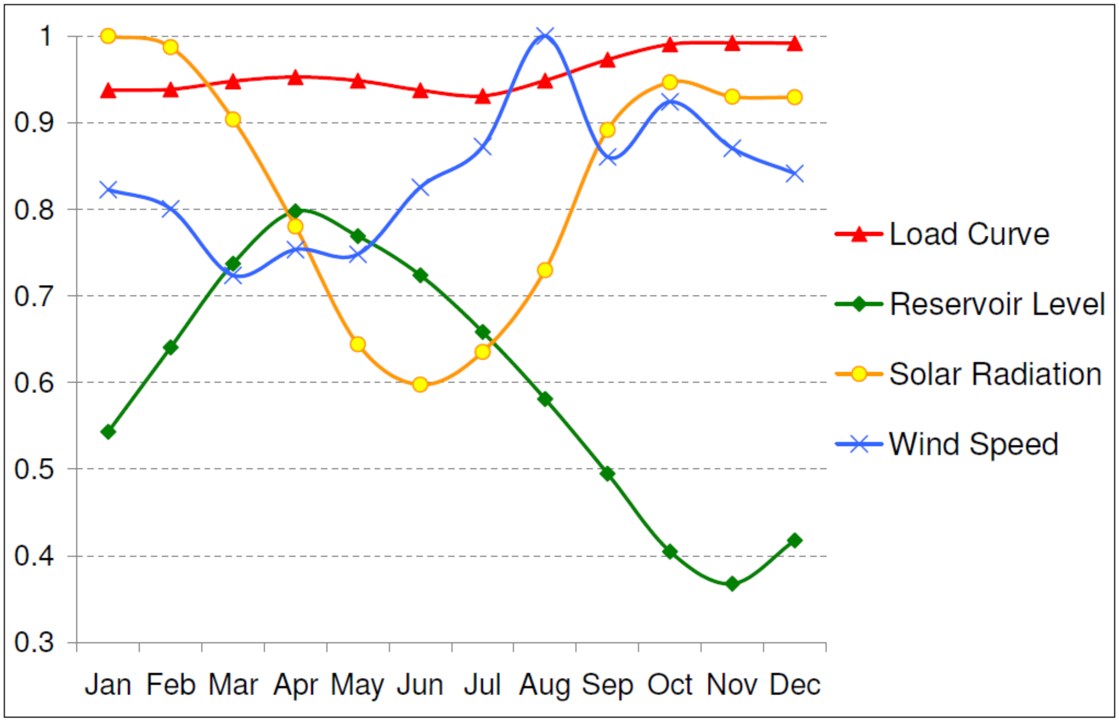


Figure 41: Monthly variation of the parameters normalized to their maximum value. Note that the NE's average reservoir (volume) level profile is normalized to the maximum reservoir capacity.

The variations of solar and wind resources, considered aggregately, have the potential to complement greatly the drop in hydroelectric availability that occurs typically between June and November. Higher and more consistent wind speeds typically occur in the dry season, when the São Francisco's flow is at its minimum (in the months when there is more scarcity of water).

In the last few months of each calendar year (October-December), the electricity demand increases to its maximum and at the same time hydroelectric reservoirs reach their lowest levels (approximately 40% of their maximum volume, in November). Fortunately in these critical months of high energy consumption and low hydroelectric availability, wind and particularly solar resources are high compared to their annual maximums (average wind speeds are approximately 85% of their maximum and solar radiation is approximately 95% of its annual maximum).

Additionally in these same critical months (October-December) the average power output from existing wind farms in Ceará reach their annual peak and wind power outputs are also high in Rio Grande do Norte as shown in figures 34 and 35.

From November the São Francisco flow rate usually begins to increase and the reservoirs begin filling again. However, if there is a lack of rainfall and a long drought occurs, reservoir levels would further drop and without alternative electricity supply sources, such as wind power, shortages in electricity supply could occur as happened in 2001.

The tariff structure of Brazilian electricity utilities could play an important role in the implementation of wind farms and solar plants in the region. In the RMS as well as in many other locations in the NE, the hourly-seasonal pricing structure reflects the reliance on hydroelectricity. The rate per megawatt differentiates between both peak and off-peak periods and between the dry season (May-Nov) and the wet season (Dec-April), during which the reservoirs fill to their highest levels (COELBA, 2011).

It can be argued that there is a clear correlation between the months of greater wind and solar energy resource availability and the months of water stress, when high (dry period) energy tariffs are in place. This coincidence is a factor in making investments in the renewable energy sector more economically viable.

13.6. Renewable energy sources compared to the electricity load curve during a typical 24 hours

A more detailed investigation focusing on the hourly variations of wind, solar resources and the electricity demand profile during a typical 24 hour day can be done using the consulted meteorological databases together with ONS load curve profile.

In Figure 42, the hourly load curve profile for the NE region (ONS, 2008) during a typical December (summer) weekday is plotted together with the hourly December average wind speeds and average solar radiation. The plotted values for respective parameters were calculated by taking the mean of all measurements of each particular hour in the entire month. Then the mean values for each respective parameter were normalized as a fraction of their maximum value (which occurred in either December or June).

The curves in Figure 43 were calculated by the same method, but show the results for a typical June (winter) weekday.

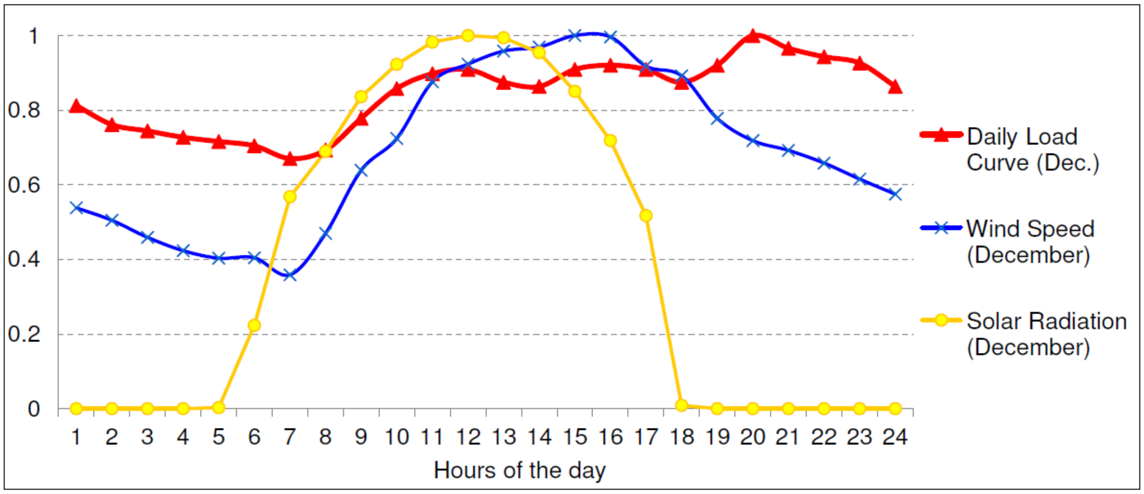


Figure 42: Summer hourly variation of the parameters normalized to their maximum value. Sources: ONS (2008), INPE (2012) and Millennium (2002).

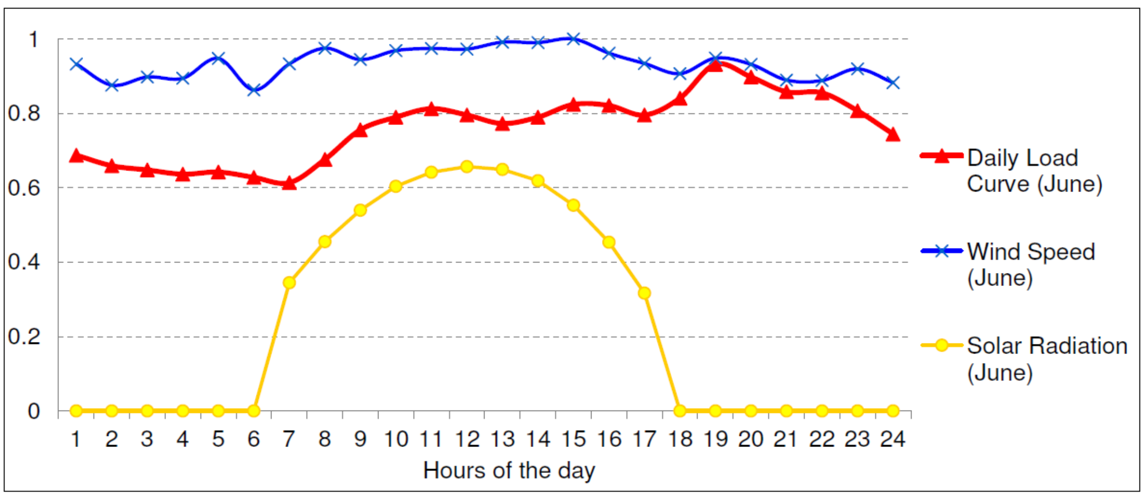


Figure 43: Winter hourly variation of the parameters normalized to their maximum value. Sources: ONS (2008), INPE (2012) and Millennium (2002).

The electrical load for a typical 24 hour weekday in the Northeast drops down to a minimum between 3:00h and 7:00h, and features its highest peaks between 19:00 and 20:00h. As a result of electricity consumption patterns, there are specific peaks at 11:00, 15:00, 19:00 and 22:00h.

Electricity distributors such as COELBA (the Electric Company of Bahia) raise energy tariffs during three consecutive hours chosen by the consumer between 17:00h to 21:00h and between 19:00h to 22:00h during daylight saving (summer time) (COELBA, 2011 and ONS, 2008).

Wind and solar energy resources correlate reasonably well to the load curve during daylight hours (see figures 42 and 43, and table 9) and have the potential to help satisfying electricity demand during the morning and early afternoon peaks.

Table 9: Pearson correlation coefficients for the hourly variation of the parameters.

Summer (Average December day)	**Solar**	**Wind**	**Combined** (Solar + Wind)
Demand (24 hour load curve)	0.043	0.740	0.308
Winter (Average June day)	**Solar**	**Wind**	**Combined** (Solar + Wind)
Demand (24 hour load curve)	0.126	0.278	0.148

Solar energy could be a good choice to support the daily rise of electricity demand that occurs in the morning from 7:00h until the second peak in demand at 15:00h, however Solar PV power would not support the main peak in demand at 19:00h (in winter) and 20:00h (in summer). In order to support the demand after the second peak, various technologies of thermal energy storage could be employed. Concentrated solar thermal plants in operation today (in Italy, Spain and the USA) are already storing energy in the form of thermal oil and pressurized molten salts to extend the daily operational period of the plants. Solana, the largest solar plant in the world (in Arizona, USA) was designed with a capacity of six hours of energy storage to cover the local demand peak, according to Abengoa Solar and the Department of Energy of the United States (DOE, 2010).

In the summer months the 24 hour average wind speed curve varies with an oscillating behaviour, with a pronounced maximum at about 15:00h and minimum at about 6:00h and it can be observed from table 9 and figure 42 that average wind speeds have a strong correlation with the 24 hour electricity load curve. Wind speeds during the winter months have much less variation and are more consistent throughout the day and night. The greater daily oscillation in summer, compared to winter, is due to sunlight heating air and land masses in the central hours of the day, which in summer causes a greater variability in the average wind speed profile during a 24 hour day. This meteorological effect is in keeping with various studies that found that wind and solar power combined are often complementary during a 24 hour day and their combined output is generally smoother with fewer severe troughs and peaks (HOICKA and ROWLANDS, 2011).

In Figure 42 it can be observed that the average daily minimum wind speed in summer coincides with the minimum in electrical demand and then from 7:00h accompanies the rise in electricity demand in the morning. Additionally the average wind speed remains relatively high until about 18h and therefore wind power could support all the daylight peaks in demand (at 11:00 and 15:00h). In summer, even though the average wind speed steadily declines from about 18:00h to midnight, wind power could still significantly support the evening peaks in consumption which occur at 19:00 and 22:00h.

However there is still concern about the reliability and security of electricity generated from wind and solar power, due to the uncertainty and intermittent nature of wind and sunlight. Neither wind nor Solar PV power can be relied upon 100% of the time, due to their sporadic nature, without some kind of energy storage or hybrid system. But in Brazil the existing hydroelectric network could also easily serve as a hybrid system. Unlike coal fired power stations, the power output from hydroelectric plants can be adjusted rapidly to increase or decrease supply as required.

14. CONCLUSION

14.1. Economic analysis

Results considering the current situation in Brazil (using a 5% discount rate) 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).

Brazil has a very low overall emissions factor due to its relatively clean electricity generation matrix compared to the world average. Considering this low emissions factor and the 2012 carbon price of only $\$10.38/tCO_{2eq}$, results in carbon credits reducing the LCOE by only \$2.13/MWh for a clean energy project. This is not nearly enough to make any impact on the competitiveness of renewable energy technology. Carbon credits and taxes would have a greater impact if their value per MWh was calculated based on the environmental externality costs from fossil fuel electricity generation. That is, it should be assumed that renewable energy projects will displace energy generated by fossil fuel plants regardless of the country's current emissions factor. The majority of Brazil's easily accessible hydroelectric resources are already saturated, therefore 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.

At a carbon price above $\$125/tCO_{2eq}$ electricity produced by coal power without carbon collection and sequestration (CCS), becomes more expensive than large scale solar technology in Brazil. On the other hand grid connected distributed PV, which is largely undeveloped in Brazil, is already competitive with retail tariffs and therefore will be viable in the near future. However this is also dependent on government policy, which to date has been ineffective in promoting PV, CSP, solar hot-water and energy efficiency in Brazil. Instead, the government is licensing and over investing in large hydroelectric projects in the Amazon which will have significant environmental impacts and transmission line costs.

With the exception of investment in hydroelectricity which is almost saturated in Brazil, the electricity generation sector has been characterized by the lack of development of renewable technologies such as solar and wind power. 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, deployment and close the economic gap that exists between these unexploited renewable technologies and traditional generation technologies.

Renewable energy sources such as wind and solar power still suffer from unfair barriers that discriminate against renewable energy. For example, rather than focussing on the LCOE, the market and decision makers often focus on the high up-front capital costs of renewable energy compared to that of conventional energy sources. It appears that budget calculations by energy infrastructure planners often don't consider the lifetime costs of fuel, operations and maintenance, transmission systems and environmental impacts of traditional generation technologies. Additionally, farm projects in Australia and the USA are often not approved by local governments because of pressure from local residents and media discrimination.

14.2. Externality analysis

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 they can also exert enormous costs on the environment, agriculture and society. If the greenhouse gas damage externality cost of the Belo Monte and Babaquara dams is taken into consideration, then Belo Monte becomes more expensive than the Caetité, Guanambi and Igaporã wind farm complex with the 5% discount rate.

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 and 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 and only 15% cheaper than the USA CSP plant. Considering the cost projections of renewable energy technologies reviewed by Hearps & McConnell (2011), CSP and PV will be cheaper than coal without CCS (and competitive with coal with CCS) by 2020 and 2025 respectively.

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. Their LCOE is still 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?

It was concluded that, in general, the length of the transmission line increases with the rated capacity of the power plant. Distributed PV systems, such as the Pituaçu Solar PV project, can be connected directly to the distribution network which saves on transmission line costs. Very large plants are often built in remote locations either because of their impacts on the environment or because this enables easy access to resources, but the disadvantage is that they require much larger and longer transmission systems which necessitate massive investments and incur significant energy losses.

14.3. Technical analysis

This study has shown that renewable energy sources in the NE region of Brazil (particularly when used in combination with each other) have a correlation with the electricity load curve during a typical 24 hour day. Both wind and solar power have the potential to assist with energy production during the morning and early afternoon peak electricity demand, while wind power could also partly support the evening peak demand.

Wind power resources are more abundant in the dry season months (May-November) when water flow into the São Francisco reservoirs is at its lowest level and solar power is more abundant when hydroelectric reservoirs are at their lowest levels. This is important as the NE, compared to the other regions of Brazil, is particularly vulnerable to water shortages either as a result of drought or from the effects of global warming and this will significantly impact on the NE´s ability to reliably supply energy from hydroelectricity. Therefore renewable energy production will help to save water during the dry season and improve energy security in the NE region. The coincidence that wind resources are greater during most of the dry season when electricity costs are higher, significantly contributes to the viability of renewable energy plants such as wind farms.

Solar energy is strongest in summer months (October-March), which coincides exactly with the months of highest demand and thus could support electricity production during daytime peak demands caused by air conditioning.

Other studies could be performed considering the correlation of demand with the uncertainties of renewable energy sources. Further study could include an analysis of the stability of energy produced from an operational wind farm in the NE and measured real-time energy output from other types of renewable energy installations over consecutive 24 hour periods. A research project that investigates the integration of a wind farm into the grid in combination with a control system that regulates the output from a hydroelectric plant to fill the gaps in wind power production would be very beneficial.

Nevertheless, despite much research and many studies that already demonstrate the economic, technical and environmental viability of renewable energy technologies, they still suffer prejudice and are avoided by large corporations and governments. As well as scientific research, more commercialisation, education, community involvement and better marketing are required for a real “clean energy revolution” to occur.

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