POLITECNICO DI MILANO

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Reliability of Electrical Generation Systems with Wind Turbines

Supervisor: Professore Giorgio Guariso

Tesi di Laurea di:

Vinicius Silva Lima 734916

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1. Double degree program

This thesis was presented in Brazil in February 2011 as the graduation work for the course of Electrical Engineering at Escola Politécnica of the Universidade de Sao Paulo (USP).

The project was overseen in Brazil by Professor Dr. José Jaime Cruz, from the Laboratory of Control and Automation (LAC), at USP.

I am greatly thankful to José Jaime for supporting me during the stage of the project that took place in Brazil, and Giorgio Guariso for providing me with a chance to work in an area that differed from the one I had been dealing with, and helping me even when I did not deserve help.

2. Abstract

Nowadays the environmental concerns are growing as fast as the problems to the mankind caused by the climate change, and one of the main needs became the bigger enemy when we realize that the electrical generation is the main source of CO2 emissions which is believed to be the mainly driver to the change in the climate.

Fighting against those emissions are made with new sources of energy, like solar, wind and hydro. But the transition needed brings some problems. One of those problems is the low reliability that the wind generation brings.

In this work is tried to achieve a better reliability in an electrical power generation grid with the presence of wind turbines by the use of fact that inside Brazilian country there is no correlation by the wind in the south and the one in the Northeast.

After this conclusion then it is measured the environmental costs of reliability's increase of using thermal generation power plants, i.e. is made a comparison by the reliability and the emissions of CO2 using different amounts of thermal and wind generation.

3. Riassunto

Oggi le preoccupazioni ambientali stanno crescendo tanto velocemente quanto crescono i problemi causati per l'aumento della temperatura nel pianetta, ed una delle principali necessità della umanità è diventato il più grande nemico quando si vede che la generazione elettrica è la principale fonte di emissioni di CO2 e questo si crede che sia il principale gas del cambio di clima nel pianetta.

Una delle forme di lottare contro queste emissioni è la generazione basata sulle nuove fonti di energia, come il solare, eolica e idrica. Però la necessaria transizione comporta alcuni problemi. Uno di questi problemi è la scarsa affidabilità che la generazione del vento porta con sé.

Questo lavoro cerca di ottenere una maggiore affidabilità in una rete di generazione di energia elettrica nella qual di trova la presenza di turbine eoliche usando il fatto che in Brasile non c'è correlazione con il vento a sud e quella del Nord-Est. E così, con la presenza delle turbine eoliche collegate posizionate in queste regione, si cerca di calcolare l'affidabilità del *grid.*

Dopo questa conclusione sono misurati anche i costi ambientali dell'aumento della affidabilità che ci porta l'uso della generazione di energia elettrica tenendo come fonte l'energia termica, cioè si fa un paragone fra l'affidabilità e le emissioni di CO2 utilizzando diverse relazione fra la produzione di origine termoelettrica e quella di origine eolica.

4. Objective

The primary goal of the present work is to assess how positioning of wind power plants may affect the reliability of the power system as a whole.

Given that wind variability is often pointed as an obstacle to achieving system reliability, regulators tend to opt for "more secure" ways of generation, which brings about certain environmental issues, like thermal power plants. This work attempts to determine how this variability can be addressed as well as how the reliability can be improved through an appropriate positioning of the power plants.

The increased use of wind power (and other renewable sources) as a means of generating electricity is directly linked to the dwindling fossil fuel sources, thus having a beneficial impact on the environment.

5. Introduction

Electrical Energy

The main goal of all energy transformations is to provide energy services that improve quality of life (e.g. health, life expectancy and comfort) and productivity (Hall et al., 2004). A supply of secure, equitable, affordable and sustainable energy is vital to future prosperity.

The wide range of energy sources and carriers that provide energy services need to offer long-term security of supply, be affordable and have minimal impact on the environment. However, these three government goals often compete.

Environmental concerns and a constant increase in fossil fuel prices are pushing research towards new and eco-friendly sources of energy. Moreover, recent legislative mover for green-houses gases limitations in the EU and similar currently under consideration around the world make the "green" generation economically more competitive against the traditional ones. The new forms of electricity generation constitute a potential way of mitigating the world's environmental issues related to the large emission of carbon dioxide (CO2), associated with the traditional carbon-based ways of producing electricity.

This work aims to combine two goals of the energy supply, the security and the minimal impact on the environment. The first goal will be measured based on the reliability of the energy source, thus generating a figure through which it will be possible to establish a comparison between a "green" generation system and a traditional one. The environment-related goal will be addressed by assessing how much energy can be produced in a "green" way without incurring loss of reliability to the final user. With that in mind and optimized the envorimental costs are going to be calculated.

Climate Change

Climate change is a change in the state of the climate than can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. (IPCC, 2007).

The warming of the climate system is unequivocal, and the linear trend of this increase in temperature is higher in the last 50 years than ever before. This temperature rise is widespread over the globe, but becomes even higher at northern latitudes. Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes. (IPCC, 2007)

The so-called greenhouse gases are the great responsible for the climate change phenomenon, with the C02, emitted by anthropogenic sources, playing a major role. This gas is so important that the amount of GHG in the atmosphere is measured through an unit called CO2 equivalent, i.e. the emissions of other gases are normalized into the equivalent emissions of CO2, based on the global warming potential characteristic of each gas. The annual emissions of CO2 gas alone have grown between 1970 and 2004 by about 80%, and it's represented 77% of total anthropogenic GHG emissions in 2004 the concentration of this gas in the atmosphere increased from 280ppm (pre-industrial value) to 379ppm in 2005. The consequences of high levels of CO2 in the atmosphere are not still perfectly known, but it is very likely that its increase may be correlated to the increase in global average temperature.

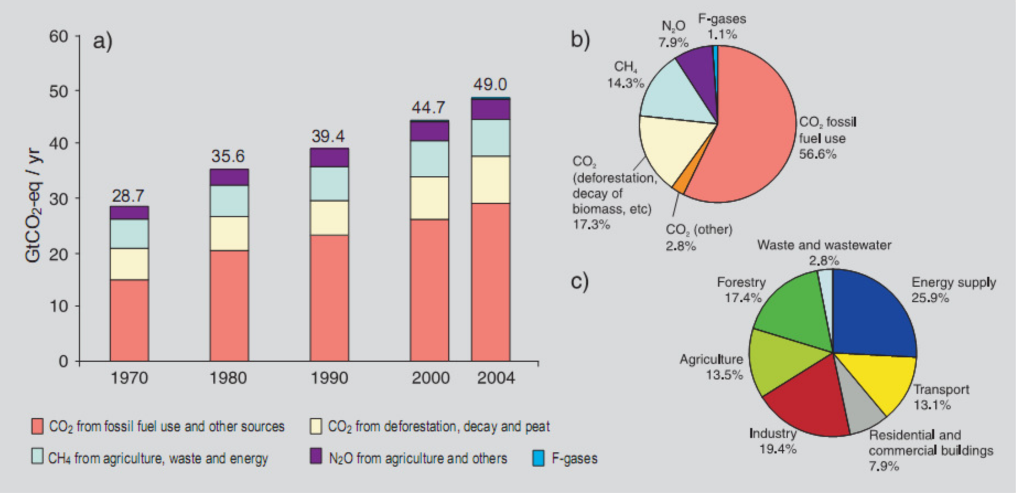


Figure 1 - (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004 (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO2-eq. (C) Share of different sectors in total anthropogenic GHGs emissions in 2004 in terms of CO2-eq (IEA, 2010)

The global problem

The largest growth in CO2 emissions has come from power generation and road transport sectors, with the industry, households and the service sector remaining at approximately the same levels between 1970 and 2004 (Figure 1.2). By 2004, CO2 emissions from power generation represented over 27% of the total anthropogenic CO2 emissions and the power sector was by far its most important source.

Energy sector reform is critical to sustainable energy development and includes reviewing and reforming subsidies, establishing credible regulatory frameworks, developing policy environments through regulatory interventions, and creating market-based approaches such as emissions trading. (IPCC, 2007). In this sector, the decrease in CO2 emissions depends on government incentives. That's because in a traditional open market the costs of the fossil fuel based generation is lower than that of the eco-friendly generation. Hence, with the recent privatization of the energy sector in most of the countries, making those companies paying for the emissions became necessary.

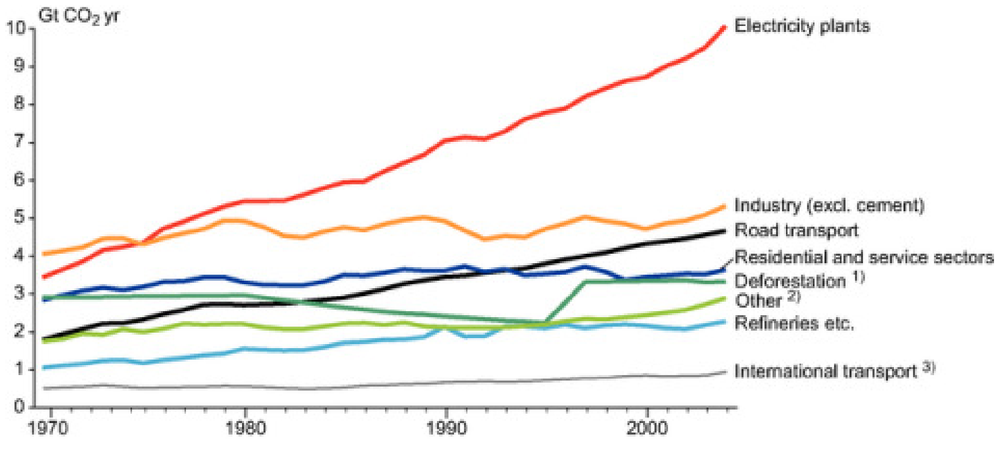
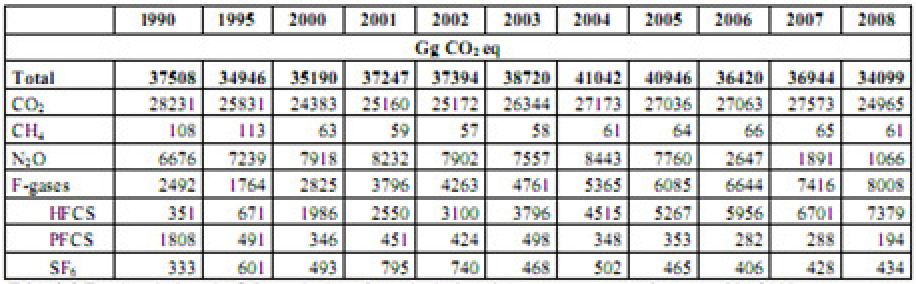


Figure 2 - Emissions of CO2 by type of industry (IPCC, 2007)

The Italian problem

In Italy in 2008 86.4 % of total emissions of GHG in CO2 equivalent came from carbon dioxide, and the total amount of emissions of this gas increased by 7.4% between 1990 and 2008; the energy sector is the largest contributor, with 83.6% of the total amount of GHG emissions. The CO2 emission of this sector has increased by about 8.2% between 1990 and 2008 and is responsible for 97.5% of the total GHG emissions. (ISPRA, 2010).

Table 1 – Total emissions in CO2-eq from industrial processes sector by gas (ISPRA, 2010)



	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008
	Gg CO_2 eq										
Total	**37508**	**34946**	**35190**	**37247**	**37394**	**38720**	**41042**	**40946**	**36420**	**36944**	**34099**
CO_2	28231	25831	24383	25160	25172	26344	27173	27036	27063	27573	24965
CH_4	108	113	63	59	57	58	61	64	66	65	61
N_2O	6676	7239	7918	8232	7902	7557	8443	7760	2647	1891	1066
F-gases	2492	1764	2825	3796	4263	4761	5365	6085	6644	7416	8008
HFCS	351	671	1986	2550	3100	3796	4515	5267	5956	6701	7379
PFCS	1808	491	346	451	424	498	348	353	282	288	194
SF_6	333	601	493	795	740	468	502	465	406	428	434

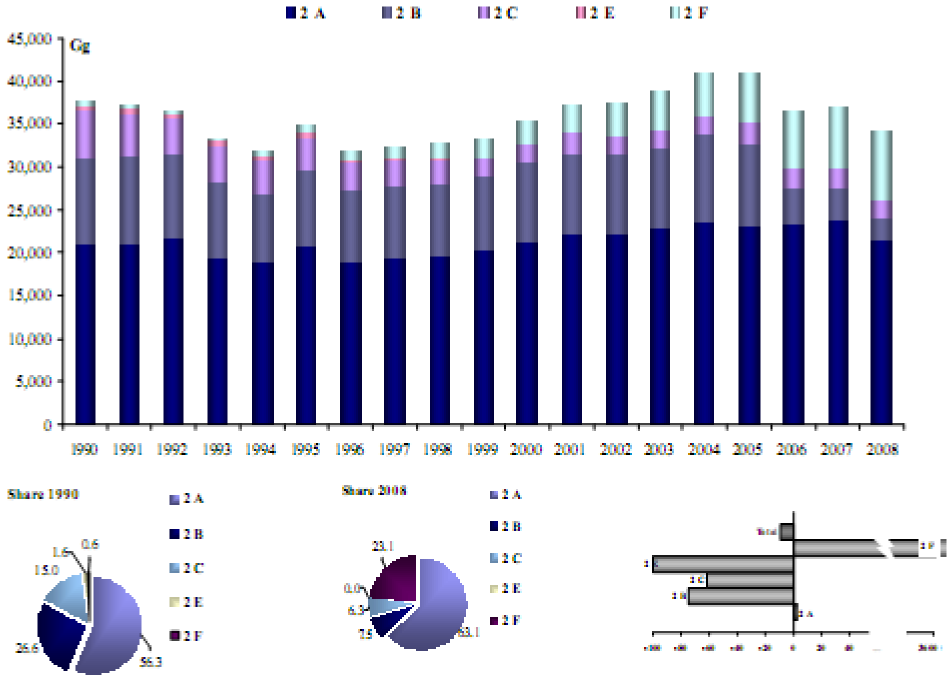


Figure 3 - Trend of total emissions in CO2-eq from industrial processes by gas (ISPRA, 2010)

Given that Italy is one of the countries that signed the Kyoto Protocol, its emissions of GHG must decrease by 6.5% until 2012, compared to 1990 levels. Considering that until 2008 the emissions had been continuously rising, efforts in the coming years must be bigger than ever. Research into cleaner technologies - in terms of GHG emissions - especially in the energy sector, becomes more and more important.

The Brazilian problem

Brazil boasts of one of the cleanest electricity generation systems in the world, predominantly based on hydro power plants, responsible for almost 70% of the Brazilian production. This fact allied to the use of biomass and gas in 80% of the thermal plants make the generation park in Brazil very clean compared to the rest of the world. (ANEEL, 2010).

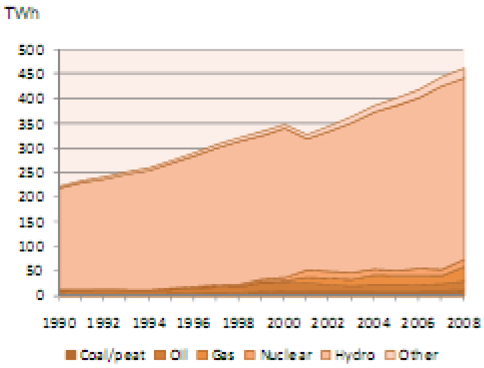


Figure 4 - Brazil: Electricity generation by fuel (ANEEL, 2010)

Nevertheless, Brazil is the third largest emitter in the world, even with only 15% of its emissions coming from the energy sector. The problem with regard to Brazilian GHG emission (85% of the total) lies in its agriculture, land-use and forestry activities, mainly the agricultural expansion in the Amazon forest.

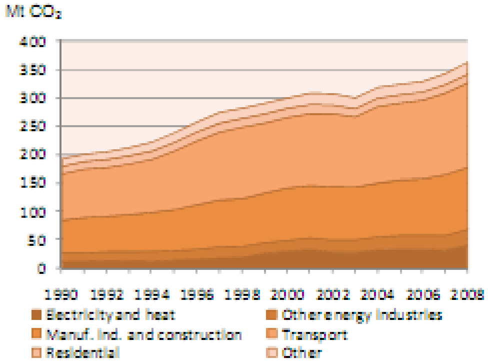


Figure 5 - Brazil: CO2 emissions by sector (ANEEL, 2010)

The new problem Brazil has been faced with results from the energy crisis (blackout) that took place in the country in 2001 and 2002. The crisis was primarily caused by a prolonged drought that led many key reservoirs to face water depletion. The fact that a major part of the country's electricity generation relies on hydro power, allied to poor planning on part of the government, brought about an energy shortage.

The government responded to the crisis by building thermo power plants, as opposed to researching into new energy technologies or improving the existing hydro power plants. Nowadays, over 1500 thermo power plants are currently being built in Brazil, which represents an increase from 14% (10 GW) of the total power supply in 2001 to 23% (25 GW) in 2009 (ANEEL, 2010). Therefore, Brazil has missed a great opportunity to develop and implement new energy technologies and to ensure the maintenance of a mostly clean electricity generation system.

Not being a member of the Kyoto Protocol, Brazil doesn't have a formal obligation to reduce its emissions, but the government is investing (a little) in the research of new technologies for energy supply, such as one based on the use of ocean waves. And some wind farms are being built, mainly in the north of the country in a total of 3 GW.

The amount of investments in wind power technology indicates that further research and greater society's awareness and support are needed to shift the government's perspective on the issue of clean energy technologies.

Main sources of energy generation

Almost all electrical energy nowadays comes from the transformation of kinetic energy into electrical energy. This process occurs by means of a generator, and the different sources of energy used to move this generator are responsible for the existence of different power plants.

The main source is the heat engine. Those engines convert the heat energy into mechanical which, in turn, will be converted in electrical energy by the turbine. The heat source constitutes another criterion according to which the power plants are divided. This division is based on the way steam is generated. The mainly sources for those plants are: Nuclear fission; Fossil fuels (as coat and oil), gas and biomass burning; solar concentrated systems.

The wind-powered energy generation is different because it directly converts kinetic energy from the moving air into electrical energy. The same principle is employed in a hydro power plant, where the water, set in motion by gravity, moves a generator.

The solar photovoltaic panels are a direct conversion from the sunlight into electrical energy by the photovoltaic effect of some semiconductors.

This work is focused on wind farms. The fossil fuel based power plants will be used as a backup source of energy so as to guarantee the reliability desired for the power grid. The minimization of its use is one of the work's objectives. As seen in the figure below, the movement towards changing world's ways of producing energy takes place rather slowly over time.

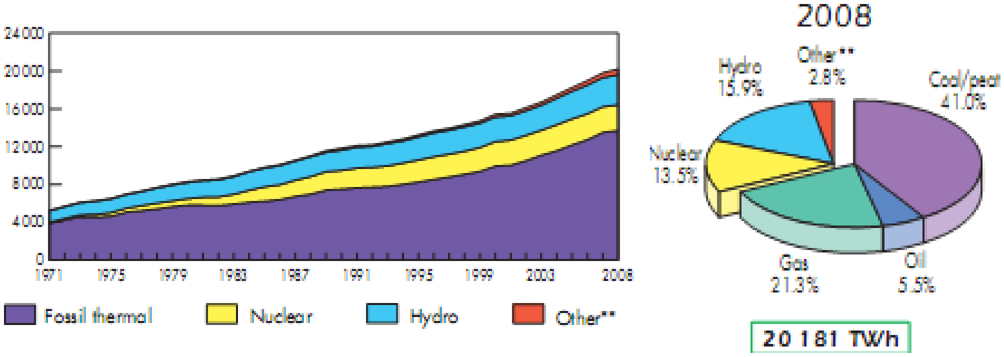


Figure 6 - Evolution from 1971 to 1008 of world electricity generation by fuel - **Other includes solar, wind, etc (IEA, 2010)

The different power plants, the environmental effects and their presence in the world nowadays are better discussed in this section.

Burning fuels power plants

In this type of energy generation the heating energy, used to convert water into steam, comes from a combustive which is burnt. Then the steam is used in a heat engine to move a generator.

This type of generation is the most used around the world as it is possible to see in the figure as well as the biggest source of GHG in the atmosphere, considering that it’s the main source of electricity and that electricity generation is the biggest responsible for the GHG emissions. Hence, this is the main objective of this work: finding ways to reduce the use of this source as much as possible by employing renewable sources instead.

There are many researchers working on making power plants based on burning combustibles less polluting. Some of these works employ a combined cycle, to improve the transformation rate (Kunitomi, et al., 2003) (Harry Habib, 2002); using biomass in the place of oil or coal (Mann, et al., 1997) (Ståhl, et al., 1998); and the use of natural gas (Bolland, et al., 1992) (Kim, et al., 2000).

However, reducing the emission levels of thermo power plants to those presented by cleaner technologies is extremely difficult.

A variety of combustibles can be used in this process. The main ones are:

Coal: Still responsible for over 40% of the world electrical production, and the biggest GHG emitter during its lifecycle also. For each kWh generated around 1000 g of CO2 is send to the atmosphere. (Gagnon, et al., 2002) This is 100 times the pollution associated with wind power.

Oil: Less important, but still a big polluter, "losing" only for coal, it generates almost 800 gCO2/kWh during its lifecycle (Gagnon, et al., 2002) and it is source for 6 % of the electrical energy generated nowadays.

Natural gas: This source is very popular, and it is the least polluting among fossil fuels, with 400 gCO2/kWh (Gagnon, et al., 2002). Such reduction in CO2 emission is achieved through optimizing burning of this combustible.

Others: include biomass and public waste. These two sources play an important role in reducing the world's reliance on fossil fuels, though their potential hasn't been fully exploited. They are also less polluting options, with the biomass generating around 30 gCO2/kWh (Pehnt, et al., 2006). The use of public waste also has the advantage of reducing the number and the sizes of the landfills.

On the other hand, the main advantage of using this kind of electricity production is the high level of reliability offered to the system. The gas turbines can follow the load in a very efficient way, powering up or down the generation. That is the reason why those types of generation are used as a backup source of energy generation to the renewable ones. Though the best option for following peak, or very strong changes of load, is the hydro power plants, the thermal ones have become the most used due to its bigger penetration in the world's biggest electricity consumers generation system (Lang, 2009).

That is why this work attempts to figure out ways to avoid, or at least reduce, the use of back-up generation, or change it for a clean one, using a grid of renewable sources of electricity.

Nuclear power plants

The principle of energy generation in a nuclear power plant is the same as that of a traditional burning fuel-powered plant. The difference lies in the way steam is produced in order to move the generator. In this case, instead of burning some fuel a controlled nuclear reaction is used.

This kind of electrical energy production nowadays represents around 6% of all world's generation; this figure is much higher in USA, France and Japan, the three biggest producers. (IEA, 2010).

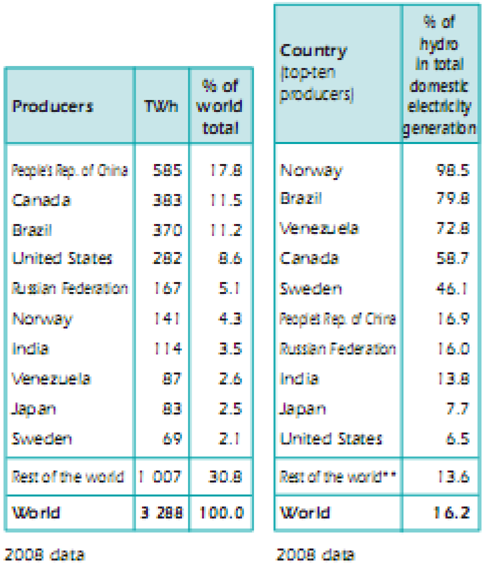
The emission levels in this process are on par with those presented by wind and solar energy, at around 9 gCO2/kWh (Sovacool, 2008). On the other hand, the potential environmental impact associated with phases of the plant's lifecycle other that the operation itself, such as the uranium mining, construction and especially the waste generated, is much larger. In his study, Sovacool arrived at 66 gCO2/kWh, which is about 6 times bigger than wind and solar generation levels, not to mention the radioactive waste generated by those plants. Hence, nuclear power technology is not considered in this work as a clean source for energy.

Hydro power plants

The most important clean generation system, with a penetration bigger than 15% and considerably low emission levels, at around 10 gCO2/kWh, the same levels as the "most famous" clean systems, such as wind and solar (Pehnt, et al., 2006).

Another great advantage of this system is the high capacity to follow the load; given that the amount of energy produced can be changed very fast, through adjusting the water flow, this type of power plant would be the most important back-up system for clean electricity generation. However, the penetration of hydro power is quite high in some developing countries whereas great consumers present much lower levels, as it's possible to see in the table below; the European countries that are in the top ten lists are only Sweden, Norway and Russia whereas United State, though being one of the biggest producers, has only 7 % of its total energy generation based on hydro power.

Table 2 - Top hydro producers 2008 (IEA, 2010)



Producers	TWh	% of world total
People's Rep. of China	585	17.8
Canada	383	11.5
Brazil	370	11.2
United States	282	8.6
Russian Federation	167	5.1
Norway	141	4.3
India	114	3.5
Venezuela	87	2.6
Japan	83	2.5
Sweden	69	2.1
Rest of the world	1 007	30.8
World	**3 288**	**100.0**

2008 data

Country (top-ten producers)	% of hydro in total domestic electricity generation
Norway	98.5
Brazil	79.8
Venezuela	72.8
Canada	58.7
Sweden	46.1
People's Rep. of China	16.9
Russian Federation	16.0
India	13.8
Japan	7.7
United States	6.5
Rest of the world**	13.6
World	**16.2**

2008 data

Another advantage of the hydro system is its storage capacity, since it is possible to pump water into the reservoirs during the periods of low load. Associating this system with wind and solar systems, so as to ensure a good load following and a storage system for the excess generation from wind and solar systems, has been the subject for various studies (Castronuovo, et al., 2004) (Korpaas, et al., 2003) . This association has a great impact on the emissions per kWh of the grid generation.

Wind farms

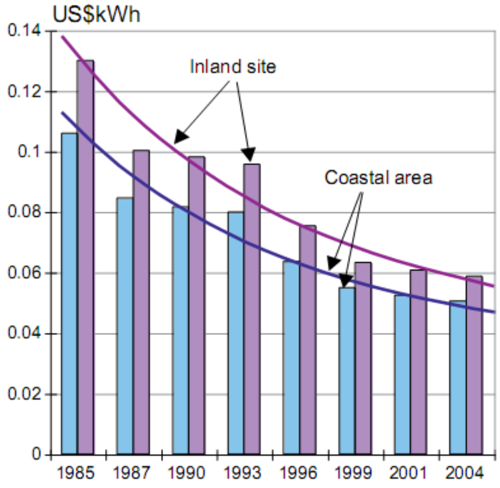


Figure 7- Development of wind-generation costs based on Danish experience (IEA, 2010)

A global study of 7500 surface stations showed that mean annual wind speeds at 80 m above ground exceeded 6.9 m/s, with most potential found in Northern Europe along the North Sea, the southern tip of South America, Tasmania, the Great Lakes region, and the northeastern and western coasts of Canada and the US. A technical potential of 72 TW installed global capacity at 20% average capacity factor would generate 126,000 TWh/yr (Archer and Jacobsen, 2005). This is five times the assumed global production of electricity in 2030 (IEA, 2006b) and double the 600 EJ potential capacity estimated by Johansson et al. (2004).

The wind power emissions are around 10 gCO2/kWh (Vestas, 2005), the same amount as the hydro power system. The advantages of wind power is the lower impact on the environment, considering that the wind generators take up less space to be installed and don’t interfere directly with the lifecycle of the place where it is installed

The fluctuating nature of the wind constrains the contribution to total electricity demand in order to maintain system reliability. To supply over 20% would require more accurate forecasting (Giebel, 2005), regulations that ensure wind has priority access to the grid, demand-side response measures, increases in the use of operational reserves in the power system (Gul and Stenzel, 2005) or development of energy storage systems (EWEA, 2005; Mazza and Hammerschlag, 2003)

The 2006 WEO Reference scenario baseline (IEA, 2006b) assumed 1132 TWh/yr (3.3% of total global electricity) of wind generation in 2030 rising to a 4.8% share in the Alternative Policy scenario. However, wind industry 'advanced' scenarios are more optimistic, forecasting up to a 29.1% share for wind by 2030 with a mitigation potential of 3.1 GtCO2/yr (GWEC, 2006). The ETP mitigation potential assessment (IEA, 2006a) for offshore wind power by 2030 ranged between 0.3 and 1.0 GtCO2/yr. In this analysis offshore wind power is assumed to reach a 7% share by 2030, mainly in OECD countries, and to displace new and existing fossil-fuel power plants according to the relevant shares of coal, oil and gas in the baseline for each region. Intermittency issues on most grids would not be limiting at these low levels given suitable control and back-up systems in place. The costs are very site specific and range from 30 US$/MWh on good sites to 80 US$/MWh on poorer sites that would also need to be developed if this 7% share of the total mix is to be met.

Solar

The proportion of solar radiation that reaches the Earth's surface is more than 10,000 times the current annual global energy consumption. Annual surface insolation varies with latitude, ranging between averages of 1000 W/m2 in temperate regions and 1200 W/m2 in low-latitude dry desert areas. Concentrating solar power (CSP) plants are categorized according to whether the solar flux is concentrated by parabolic trough-shaped mirror reflectors (30–100 suns concentration), central tower receivers requiring numerous heliostats (500–1000 suns), or parabolic dish-shaped reflectors (1000–10,000 suns). The receivers transfer the solar heat to a working fluid, which, in turn, transfers it to a thermal power-conversion system based on Rankine, Brayton, combined or Stirling cycles. To give a secure and reliable supply with capacity factors at around 50% rising to 70% by 2020 (US DOE, 2005), solar intermittency problems can be overcome by using supplementary energy from associated natural gas, coal or bioenergy systems (IEA, 2006g) as well as by storing surplus heat. Solar thermal power-generating plants are best suited for lower latitudes areas with high levels of direct insolation. In these areas, 1 km2 of land is enough to generate around 125 GWh/yr from a 50 MW plant at 10% conversion of solar energy to electricity (Philibert, 2004). Thus about 1% of the world's desert areas (240,000 km2), if linked to demand centers by high-voltage DC cables, could, in theory, be sufficient to meet total global electricity demand as forecast out to 2030 (Philibert, 2006; IEA, 2006b). CSP could also be linked with desalination in these regions or used to produce hydrogen fuel or metals.

The most mature CSP technology is solar troughs with a maximum peak efficiency of 21% in terms of conversion of direct solar radiation into grid electricity. Tower technology has been successfully demonstrated by two 10 MW systems in the USA with commercial development giving long-term levelized energy costs similar to trough technology. Advanced technologies include troughs with direct steam generation, Fresnel collectors, which can reduce costs by 20%, energy storage including molten salt, integrated combined-cycle systems and advanced Stirling dishes. The latter are arousing renewed interest and could provide opportunities for further cost reductions (WEC, 2004d; IEA 2004b).

Concentrating solar power (CSP) and photovoltaics (PV) can theoretically gain a maximum 1–2% share of the global electricity mix by 2030 even at high costs. The 2006 WEO Reference scenario (IEA, 2006b) estimated 142 TWh/yr of PV generation in 2030 rising to 237 TWh in the Alternative scenario but still at <1% of total generation. EPRI (2003) assessed total PV capacity to be 205 GW by 2020 generating 282 TWh/yr or about 1% of global electricity demand. Other analyses range from over 20% of global electricity generation by 2040 (Jäger-Waldau, 2003) to 0.008% by 2030 with mitigation potential for both PV and CSP likely to be <0.1 GtCO2 in 2030 (IEA, 2006a) the calculated minimum costs for even the best sites resulted in relatively high costs per ton CO2 avoided. The baseline (IEA, 2004a) gave the total solar potential as 466 TWh or 1.4% of total generation in 2030. In this analysis, generating costs from CSP plants could fall sufficiently to compete at around 50–180 US$/MWh by 2030 (Trieb, 2005; IEA, 2006a). PV installed costs could decline to around 60–250 US$/MWh, the wide range being due to the various technologies being installed on buildings at numerous sites, some with lower solar irradiation levels. Penetration into OECD and EIT markets is assumed to remain small with more support for developing country electrification.

6. Reliability

Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered. [Bagowsky, I., Reliability Theory and Practice, Prentice-Hall (1961)]

Taking this definition it's possible to infer that probability is the most important numerical parameter of reliability. Meanwhile the other important parts of the definition call our attention to engineering decision, as performance, operational conditions and period of time. Those aren't problems related to the probability theory.

On the other hand, there are many others indices used to measure the possible problems of a system, and the term 'reliability' has been used as a generic way to describe the combination of those indices.

Some of those indices are: Number of failures in the studied time, duration of failures, time between those failures, etc. By calculating those terms, it is possible to determine whether the system has an acceptable performance.

The assessment of whether a performance is acceptable or not is nowadays based on probabilistic values. There is a distribution of values to the parameters that are measured or calculated, and comparing the distribution of the set and the indices using some probabilistic techniques makes it possible to evaluate the overlapping areas, therefore enabling the determination of the reliability index required, as illustrated in the figure below:

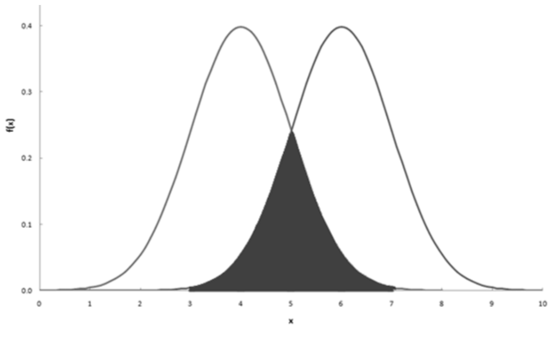


Figure 8 - Distribution comparison (Billinton, et al., 2002)

In order to have a reliable system the value of the overlapping must not exceed a specific limit. Usually this limit is established by the government, resulting in penalties if not satisfied.

An appropriate reliability index is usually determined using probability theory. To find the right approach to the system analyzed it is necessary to think of a series of assumptions, and the validation of the indices found depends directly on the understanding of the system. Understanding how it operates, to then indentify the possible failures. With the knowledge of the system the choice of the reliability approach can be made. There are two main techniques to evaluate the reliability of a system, analytical and simulation. In the first the model of the system is the base to the evaluation of the reliability. The other option consists of performing the Monte Carlo simulation, whereby the reliability is assessed through simulating the process based on a random behavior.

Frequency and duration techniques.

By using the Markov chain it is possible to calculate the probability of the power system being in one of the possible states. And so the contribution of each state of the system to the overall situation. With this technique it is possible to evaluate the frequency of encountering a system in a given state, improving the reliability indices of this system.

The basic concepts of this technique are best described in terms of a single repairable component. The space state diagram of this system is shown in figure

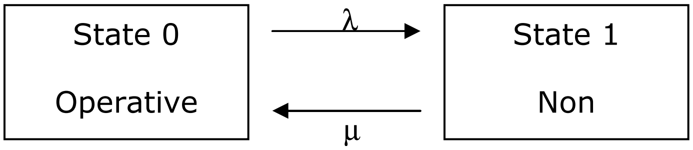


Figure 9 - State diagram

Considering that we have only two possible situations, Available (1) or Unavailable (0) the figure shows timing for the situations of failures and repairs.

Mean time between failures (MTBF), Mean time to failure (MTTF), Mean time to repair (MTTR). Where:

MTBF = MTTR + MTTF.

It is also possible to have the values Failure Rate (λ) and Repair Rate (μ). Where:

$$\lambda = \frac{1}{MTTF}$$

$$\mu = \frac{1}{MTTR}$$

$$f = \frac{1}{MTBF}$$

Where f is the frequency of encountering a system state, which, in this case, as there are only two states, is the same for the both of them.

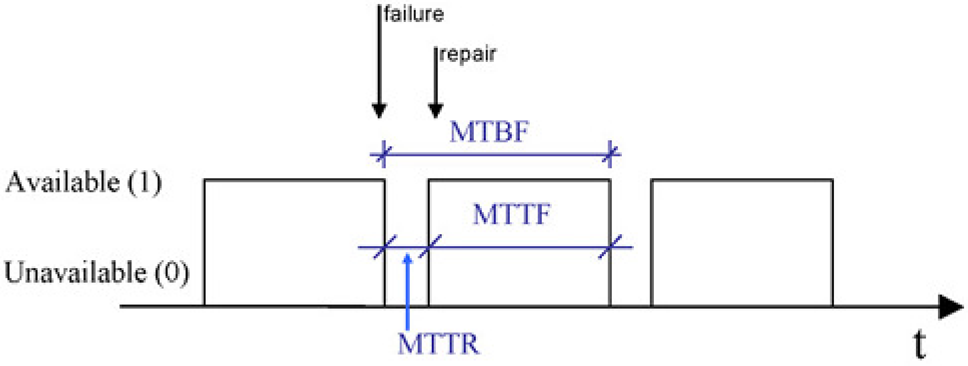


Figure 10 - Possible States (Billinton, et al., 2002)

The probability of being in the state 0 (operative) can be calculated as

$$P_0 = \frac{\mu}{\mu + \lambda}$$

Meanwhile the state 1 has as probability

$$P_1 = \frac{\lambda}{\mu + \lambda}$$

The importance of calculating the frequency and duration of the states of the system can be demonstrated, for example, by considering that the probability for each state of a system with failure rate equal to λ and repair rate μ are exactly the same as a system where those parameters are 2λ and 2μ. The second one though has failures twice as frequent as the first, which, in most cases, affects the reliability of the system.

It's possible to calculate the relation with the frequency of the system as follows: the probability of the system being in a state is the mean time in that state divided by the cycle time for that state to occur. This procedure works for any repairable system even those with more than 2 states (Billinton, et al., 1996).

From the equation it's possible to change and arrive at:

$$P_o = \frac{\mu}{\mu+\lambda} = \frac{MTTF}{MTTF+MTTR} = \frac{MTTF}{MTBF} = \frac{f}{\lambda}$$

With the same procedure for P_1:

$$P_1 = \frac{f}{\mu}$$

From those equations:

$$f = P_0\lambda = P_1\mu$$

Putting in words: frequency of encountering in a state is equal to the probability of being in the state divided by the rate of departure from the state which is equal to the probability of not being in the state divided by the rate of entry into the state (Billinton, et al., 2002).

This applies only to long term or average behavior. It works for any system with no time dependency. Thus if f(S) is the frequency, P(S) is the probability of being into the state, $\bar{P}(\bar{S})$ is the probability of NOT being into the state, $\lambda_d(S)$ is the rate of departure and $\lambda_e(S)$ is the rate of entry into the state.

$$f(S) = P(S)\lambda_d(S) = \bar{P}(\bar{S})\lambda_e(S)$$

Finally

$$MTTF(S) = \frac{1}{\lambda_d(S)} = \frac{P(S)}{f(S)}$$

It means that the duration of the state is the inverse of the rate of departure of this state, and also that this duration is the probability of being in the state divided by the frequency of encountering the state. This becomes very useful when states come combined or cumulated to describe systems.

Loss of load indices

Using the technique of modeling the generation system, and convolving it with a model of the load it's possible to create a system risk index. As the number of models which can be created is really high, the same happens to those indexes.

One model extensively used is one where each day is represented by its daily peak load. This, combined with the system capacity outage probability, gives the expected risk of loss of load.

It's important to remember that there is a difference between "capacity outage" and "loss of load". The first refers to the capacity of the system which is not generating energy in that moment, and when this outage surpass the load expectation this difference is called loss of load.

The combination can be used to create a probability table to obtain the expected number of days where the capacity is smaller than the load. The index in this case is called Loss of Load Expectation (LOLE) (Billinton, et al., 1996).

$\mathrm{LOLE} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{P_i}(\mathrm{C_i} - \mathrm{L_i})$ Days/period

Where, $\mathrm{C_i}$ = available capacity on day i.

$\mathrm{L_i}$ = forecast peak load on day i.

$\mathrm{P_i}(\mathrm{C_i} - \mathrm{L_i})$ = probability of loss of load on day i.

Loss of energy indices

The LOLE approach uses the daily peak loads to calculate the expected number of days in the period that the load exceeds the capacity. The area under the load duration represents the energy utilized during that period, thus area can be used to calculate an expected energy not supplied due to insufficient installed capacity. This relation can also be represented as ratio which is called "energy index of unreliability" with no unit. However this ratio is extremely small and comes more used subtract it from the unity. This new parameter is called "energy index of reliability".

The probable energy curtailed is $E_k P_k$ and the total amount of energy is the loss of energy expectation (LOEE) (Billinton, et al., 1996).

$$\mathrm{LOEE} = \sum_{k=1}^{n} E_k P_k$$

Where:

O_k = capacity outage;

P_k = probability of capacity outage equal to O_k

E_k = energy curtailed by capacity outage O_k

This amount can be normalized to the total energy, the area under the load curve, called E.

$$\mathrm{LOEE}_{\mathrm{p.u.}} = \sum_{k=1}^{n} \frac{E_k P_k}{E}$$

And so it's possible to define the energy index of reliability (EIR).

$$\mathrm{EIR} = 1 - \mathrm{LOEE}_{\mathrm{p.u.}}$$

The value of the energy curtailed can also be used to determine the expected energy produced by each unit and so provides an approach to production cost modeling.

7. Mathematical modeling

A very important step when calculating the reliability of a power system is simulating the hourly characteristics of the power source. In the present case, these sources will be both wind and traditional thermal and hydro sources. Those simulations have been done based on different sources.

Wind

Wind represents an indirect form of the originating energy of the sun and the rotational Earth movement. The non-uniform heating of the terrestrial surface, as well as the unequal thermal characteristic of the terrestrial and aquatic masses of the planet altogether combined with the rotational movement, creates the air movement that we know as wind, which circulates around the terrestrial surface following a global circulation pattern.

For wind power quantification three basic characteristics are needed: wind speed and direction, the topographic characteristics of the study area and the air density [5]. The most relevant parameter is the wind speed, since wind power is a proportional variable to the cube of wind speed as show in (1).

$$P = \frac{1}{2}\rho * A * V^3$$

Where ρ is the air density (kg/m3), V is the wind speed (m/s) and A is the rotor area (m2).

A wind turbine is a device that performs two transformations. Firstly, it takes the kinetic energy of the wind and converts it into a rotational movement by means of a rotor. This rotor is attached to a generator which takes this rotational movement and converts it into electrical energy. This transformation is more complex than it seems, involving many areas of knowledge as electrical, mechanical, aerodynamically, control systems, ecc. (Heier, 1998).

The variety of turbines in the market nowadays is tremendous. With the electromechanical conversion system in mind though, which is what really matters in the present case, three types comes out are worthy of attention.

The first one is called constant wind turbine and consists of a directly grid coupled squirrel cage induction generator, the coupling rotor-generator is made trough a gear box. Most of these turbines are designed to experience an aerodynamic efficiency decrease as the wind speed increases, in order not to allow the mechanical power extracted from the wind to become too large. By making use of such effect (called stall effect), a control system is unnecessary.

The second one is the variable speed wind turbine with doubly fed (wound rotor) induction generator. In this case the control of the rotor speed is made by pitching the rotor blades. The rotor-generator system is made trough a gear box and the main difference from the first type is that the generator is connected back-to-back voltage source.

The third concept uses a direct drive synchronous generator and it is also a variable speed wind turbine. The synchronous generator can have a wound rotor being excited by permanent magnets. The grid coupling is made by a back-to-back voltage source converter or a diode rectifier and a voltage source converter. The use of a synchronous generator makes it unnecessary to have a gear box, as it is a multi pole low speed generator. As with the second case, the high speed control is made by the pitching of the blades (Archer, et al., 2005).

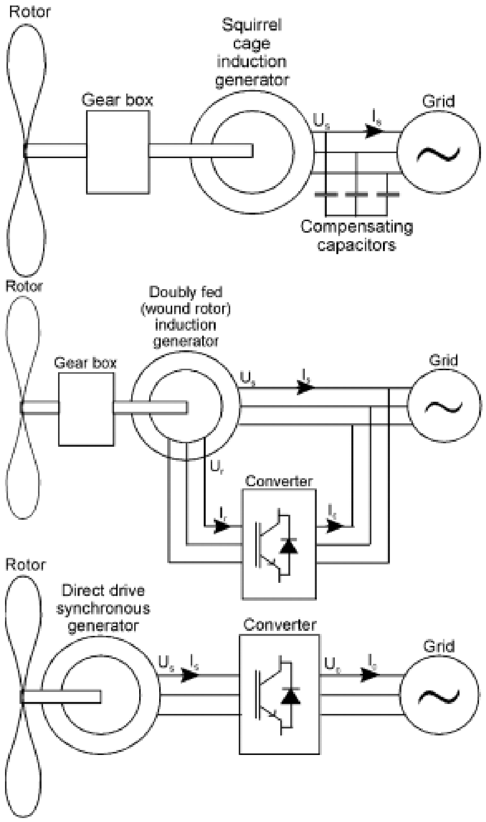


Figure 11 - Types of wind-generators

Wind-powered electricity generation has expanded significantly all over the world. By the end of 2009, the capacity of this kind of generation was 159.2 gigawats (GW). That represents an increase of 38.3 GW compared to 2008 (WWEA, 2009). As the penetration of this kind of generation increases, further studies on how this penetration affects the current system become more and more necessary. The coupling of big wind farms with the power grid may bring about differences that must be analyzed.

The potential for this growth was studied in 7500 surface stations around the world showed a technical potential of 72 TW with a global capacity at 20% of average capacity factor the generated power would br 126,000 TWh/yr (Archer, et al., 2005). This is five times the assumed global production of electricity in 2030 (IEA, 2004)

The fluctuating nature of the wind constrains the contribution to total electricity demand in order to maintain system reliability. To supply over 20% would require more accurate forecasting (Giebel, 2005), regulations that ensure wind has priority access to the grid, demand-side response measures, increases in the use of operational reserves in the power system (Gul and Stenzel, 2005) or development of energy storage systems (EWEA, 2005; Mazza and Hammerschlag, 2003)

The turbine generator output characteristic

The electrical output of the wind energy conversion systems (WECS) depends on three things: the wind characteristics, the performance of the turbine and the efficiency of the electric generator. Those three must be combined to obtain a probabilistic profile of the WECS output. There are a few main wind speeds. The first one is called cut-in speed and it is the wind speed that starts producing electricity. The electricity generation grows in a non-linear curve until the so-called rated speed. Afterwards, it remains constant until the control turns off the generator for safety reasons at the cut-out or furling speed. Due to variations in the wind speed, the periods inside the non linear area can be more than half of total (Chowdhury, 2005) (Liu, et al., 2008) (Billington, et al., 1993) (Giorsetto, et al., 1983) (Wang, et al., 2001). A typical WECS electrical output curve is show in figure bellow.(Wen, et al., 2009)

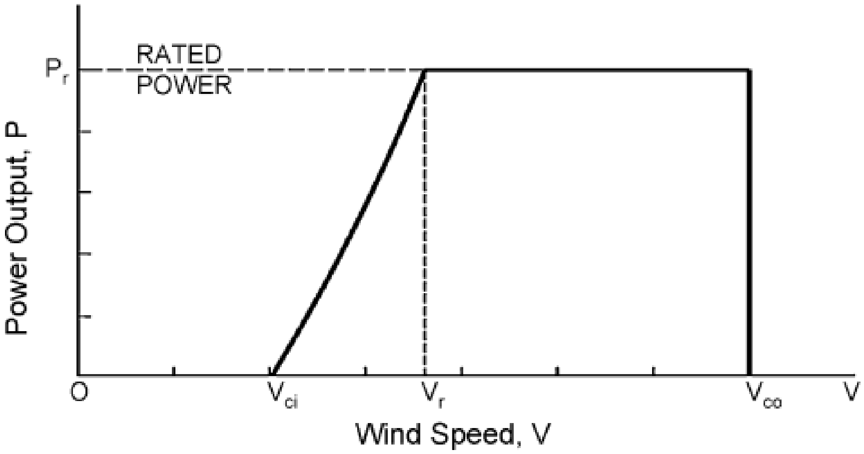


Figure 12 - Typical WECS output characteristic

The parameters in the figure are: p_r = rated power output; v_{ci} = cut-in wind speed; v_r = rated wind speed; v_{co} = cut-out wind speed.

The WECS power output (p_{out}) can be calculated as:

$$p_{out} = \begin{cases} 0 & 0 \le v \le v_{ci} \text{ or } v \ge v_{co} \\ (A + Bv + Cv^2)p_r & v_{ci} \le v \le v_r \\ p_r & v_r \le v \le v_{co} \end{cases}$$

Where the constants A, B and C can be found as follow:

$$A = \frac{1}{v_{ci} - v_r}\left[v_{ci}(v_r + v_{ci}) - 4(v_{ci} \times v_r)\left(\frac{v_{ci} + v_r}{2v_r}\right)^3\right]$$

$$B = \frac{1}{(v_{ci} - v_r)^2}\left[4(v_{ci} + v_r)\left(\frac{v_{ci} + v_r}{2v_r}\right)^3 - (v_r + 3v_{ci})\right]$$

$$C = \frac{1}{(v_{ci} - v_r)^2}\left[2 - 4\left(\frac{v_{ci} + v_r}{2v_r}\right)^3\right]$$

(Giorsetto, et al., 1983)

The practical output for the turbine used in his work is

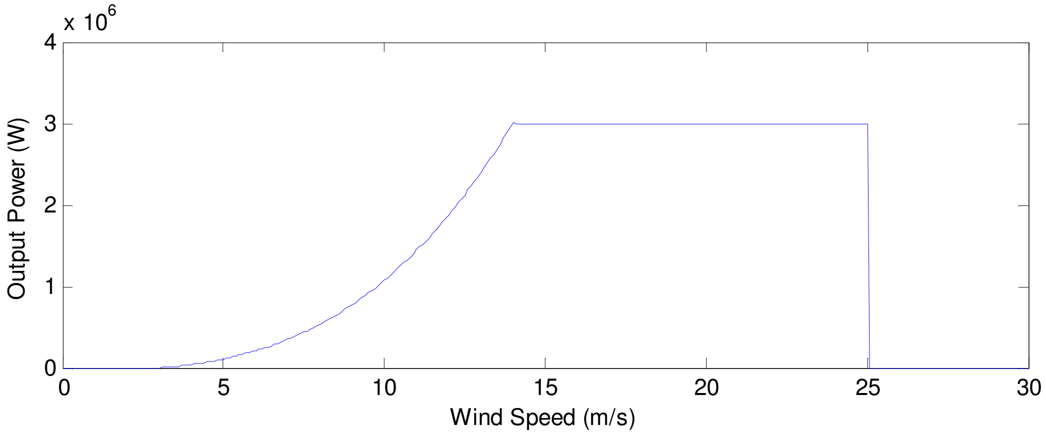


Figure 13 - Simulated WECS output characteristic

Modeling the wind

First Method – ARMA system:

Using the systems previously mentioned to simulate the wind speed and standard deviation. From the data there are:

OW_t = the observed wind speed at hour t;

μ_t = the mean observed wind speed at hour t,

σ_t = the standard deviation of observed wind speed at hour t,

μ = the mean wind speed of all the observed data,

σ = the standard deviation of wind speed obtained from all the observed data and

SW_t = the simulated wind speed at hour t.

Using that

$$y_t = f(OW_t, \mu_t, \sigma_t, \mu, \sigma, \dots) = \frac{OW_t - \mu_t}{\sigma_t}$$

Then y_t can be used to generate an ARMA (Auto-Regressive and Moving Average) time-series model:

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \dots + \phi_n y_{t-n} + \alpha_1 - \theta_1 \alpha_{t-1} - \theta_2 \alpha_{t-2} - \dots - \theta_m \alpha_{t-m}$$

where $\phi_i (i = 1, 2, \dots, n)$ and $\theta_j (j = 1, 2, \dots, m)$ are the auto-regressive and moving average parameters of the model, respectively $\{\alpha_t\}$ is a normal white noise process with zero mean and a variance of σ_a^2.

After having the time model it is possible to simulate the wind speed with:

$$SW_t = f^{-1}(y_t, \mu_t, \sigma_t, \mu, \sigma, \dots) = \mu_t + \sigma_t \cdot y_t$$

I.e. $f^{-1}(\cdot)$ is the inverse function of $f(\cdot)$.

Two problems must be solved when using the ARMA system. The first one is to search for the parameters. The way to solve this problem is the least square approach. First step consists of estimating the initial values and then searching for optimal parameters.

The second problem is to calculate the order (n, m) of the ARMA system using the fact that any stationary stochastic system can be approximated as closely as needed by an ARMA model of order $(n, n-1)$ (Pandit, et al., 1983). The procedure used to solve the reduced problem of finding n is the following:

Step 1. Let $n = 2$; fit the ARMA $(n, n-1)$ model least square approach, calculate the residual sum of squares of the model and designate it as RSS$(n, n-1)$.

Step 2. Fit the ARMA $(n+1, n)$ model and calculate the residual sum of square RSS$(n+1, n)$ using the same approach as above.

Step 3. Let

$$F = \frac{RSS(n, n-1) - RSS(n+1, n)}{2} \div \frac{RSS(n+1, n)}{N - (2n+2)}$$

in which N is the total number of observations. Perform the following comparisons using the value of$F$:

I If $F > F_p\,(2, N - r)$, where $F_p\,(2, N - r)$ denotes the F-distribution with 2 and $N - r$ degrees of freedom at probability level p, then the improvement in the residual sum of squares in going from ARMA$(n, n-1)$ to ARMA$(n+1, n)$ is significant at the $(1 - p) \times 100\%$ significance level and therefore there is evidence that the ARMA$(n, n-1)$model is inadequate; go to Step 4.

II If $F < F_p\,(2, N - r)$, then the ARMA$(n, n-1)$model is adequate at the level of significance, go to Step 5.

Step 4. Set $n + 1 \rightarrow n$, go to Step 2.

Step 5. Fit a pure AR(n) model and use the F-criterion to check the adequacy of the model AR(n). If it is adequate, AR(n) can be used as a possible substitute model for ARMA(n, $n-1$); if it is not adequate, fit the desired forms of models AR(n') where $n' > n$ until an insignificant F value is reached. The last AR (n') model can be used as a possible substitute for ARMA($n, n-1$).

Second Method – Weibull stochastic system:

Another way to describe the wind speed, as it changes continuously, and to obtain estimations in long term are the statistical methods. The Weibull probability density function has been widely used in the field of engineering to describe variations of the wind speed. The Weibull model can be obtained using.

$$f(v) = \frac{\alpha}{\beta}\left[\frac{v}{\beta}\right]^{\alpha-1} * e^{\left(-\left(\frac{v}{\beta}\right)^{\alpha}\right)}$$

Where "v" represents wind speed, "α" is the shape factor and "β" is the scale factor of Weibull probability density function (Ortiz, et al., 2000).

With the data field of wind speed measurements, it is possible to obtain the representative parameters of the Weibull probability density function from the wind speed average defined as the average arithmetic of the measurements.

Those measures and the factors of the Weibull distribution are widely used for wind analyses, and because of that there are several wind maps of regions where it is possible to find the values of the scale and the shape factor of that region.

Two of those maps were used in this work. The first one is from the northeast state of Rio Grande do Norte and the second from the south state of Rio Grande do Sul. See Append 1. In this work the factors are: Northeast shape 4.4 and scale 9.5. And for the south shape 2.5 and scale 8.5.

This method was used in this work because the amount of data is bigger and more reliable than using data for creating an ARMA system.

Mathematical modeling for traditional power generation

The values associated with traditional power sources in this work were extracted from the work of Billinton, where he turns the IEEE Reliability Test System (IEEE, 1979) into a friendlier test for educational proposes. The power sources used in this work are:

Table 3- Conventional generators data (R. Billinton, 1989)

Unit size (MW)	Type	N° of units	Forced outage rate	MTTF (hr)	Failure rate per year	MTTR (hr)	Repair rate per year	Scheduled maintenance Wk/yr
5	hydro	2	0.010	4380	2	45	198	2
10	Thermal	1	0.02	2190	4	45	196	2
20	Hydro	4	0.015	3650	2.4	5	157.6	2
20	Thermal	1	0.025	1752	5	45	195	2
40	Hydro	1	0.02	2920	3	60	147	2
40	thermal	2	0.03	1460	6	45	194	2

Mathematical modeling for the load

The load model follows the IEEE Reliability Test System (IEEE, 1979), which presents definitions that take into account the seasonality of power consumption along the year, weeks and during the days. By changing the peak load, it is possible to obtain the hourly load for the entire year.

With a peak load of 185MW the curve used in this work is

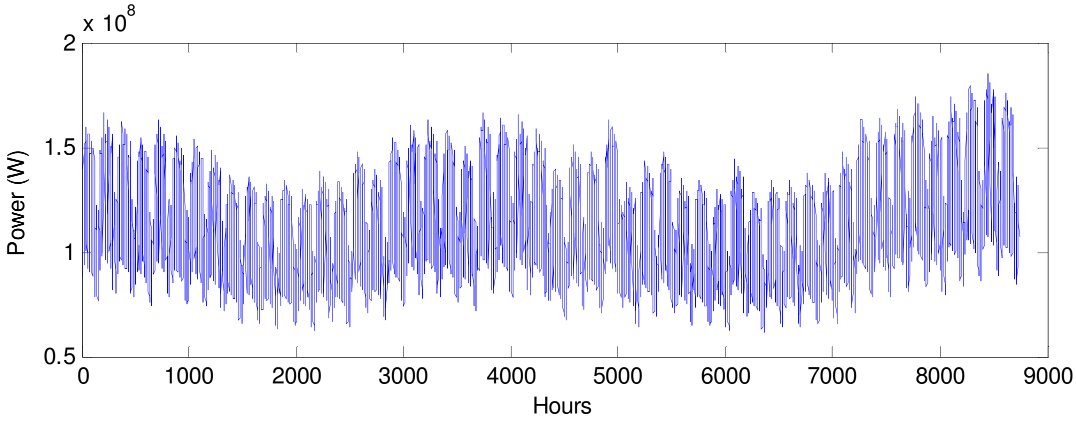


Figure 14- Simulated hourly load

8. Simulation

Monte Carlo Simulation

In this work, the usual generators showed below are considered to work only in on-off stages or the generator is UP and then it produces its full power or is DOWN and without power production.

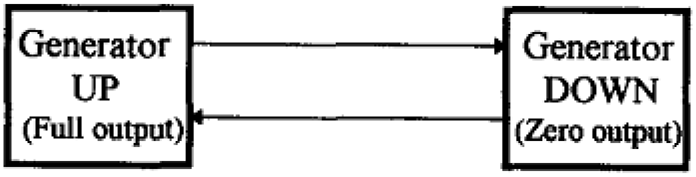


Figure 15 - Possible States

The shift between those two situations is achieved by using the Monte Carlo method, i.e. for each hour of the simulation a random number is generated and according with this number and the state where the generator is, it can change states or not. This change of state is controlled by the failure and repair rate of the generators as indicated in the model of the conventional generators Table 3- Conventional generators data.

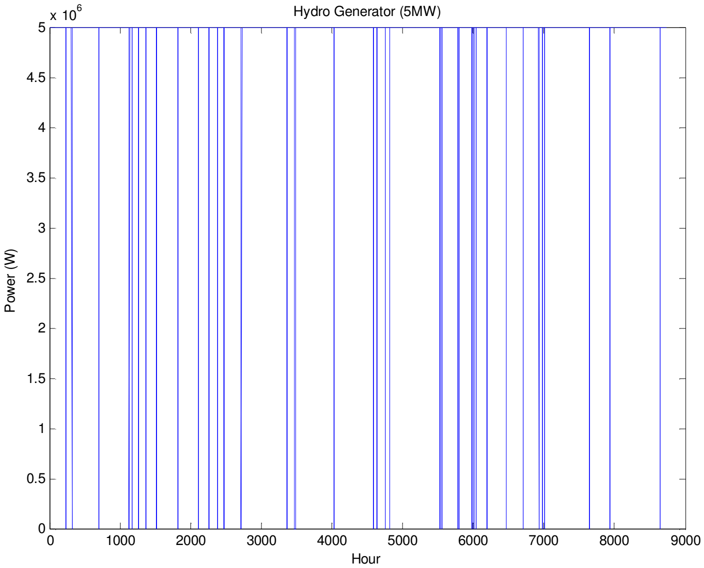
The simulation of one year power output (hourly) for each of the usual power generators used in this work are those, clearly as in this work the Monte Carlo simulation is used, for each simulation a different result is coming out. It is obviously by the graphs the two-stage nature of those generators (in this work).

The results indicate clearly the considerable difference between the amount of CO2 emitted by the thermal power plants and the hydro ones. The total power generated along the year, as it depends only on the unit size, almost doesn't change with the type of the generator.

- Hydro generators of 5 MW (each)

  Total power along the year: 43.210 GWh

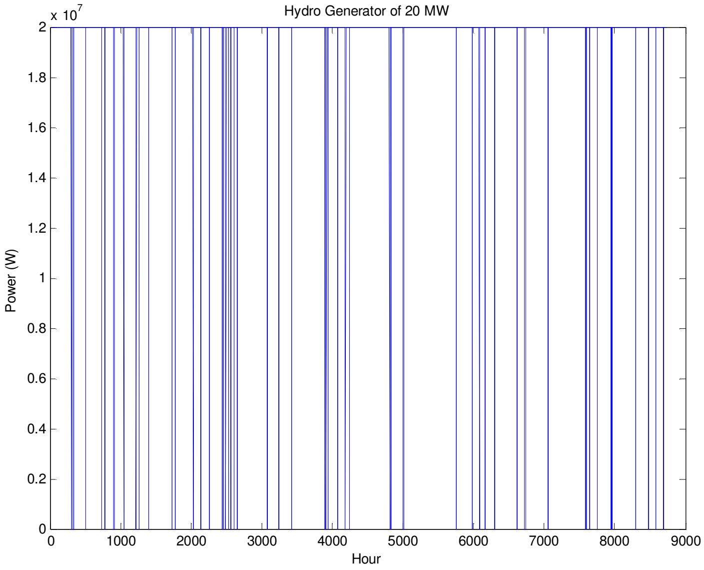
  Total CO2 emissions: 432 tons



- Hydro generators of 20 MW (each)

  Total power along the year: 172.44 GWh

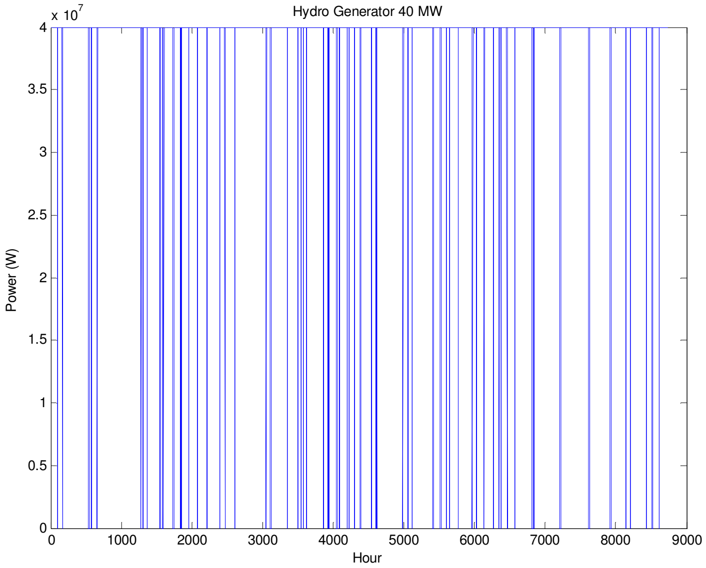
  Total CO2 emissions: 1724 tons/year



- Hydro generator of 40 MW

  Total power along the year: 341.04 GWh

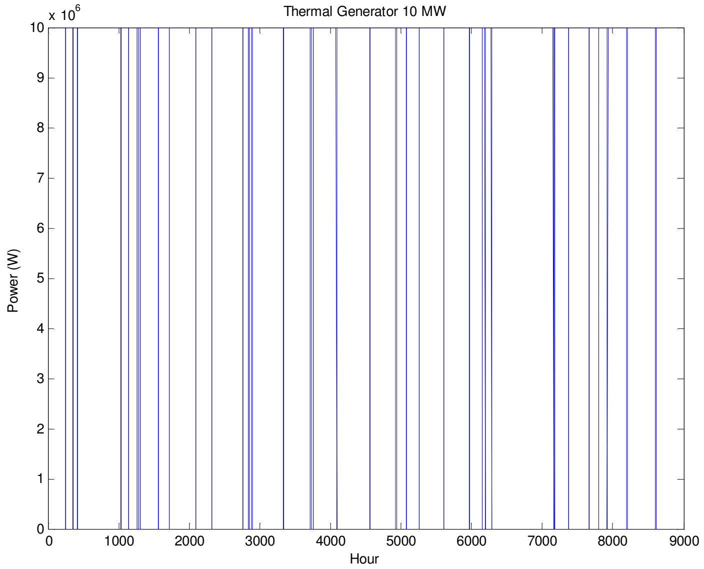
  Total CO2 emissions: 3410 tons/year



- Thermal generator of 10 MW

  Total power along the year: 85.92 GWh

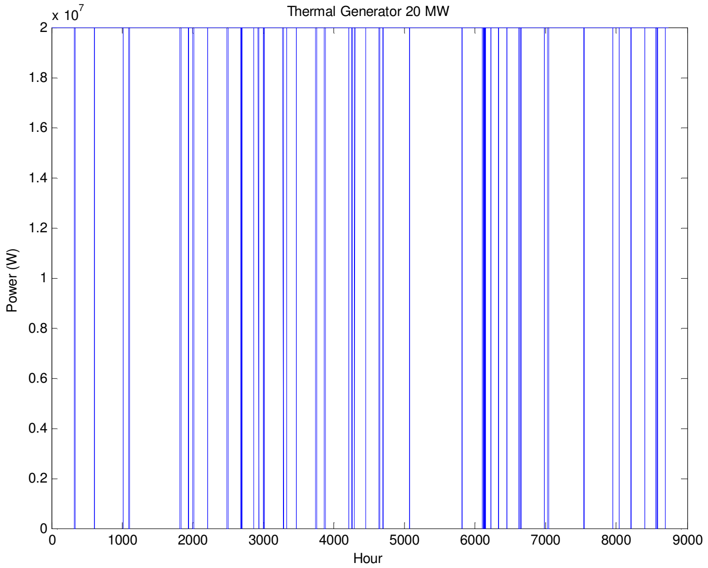
  Total CO2 emissions: 34368 tons/year



- Thermal generator of 20 MW

  Total power along the year: 170.12 GWh

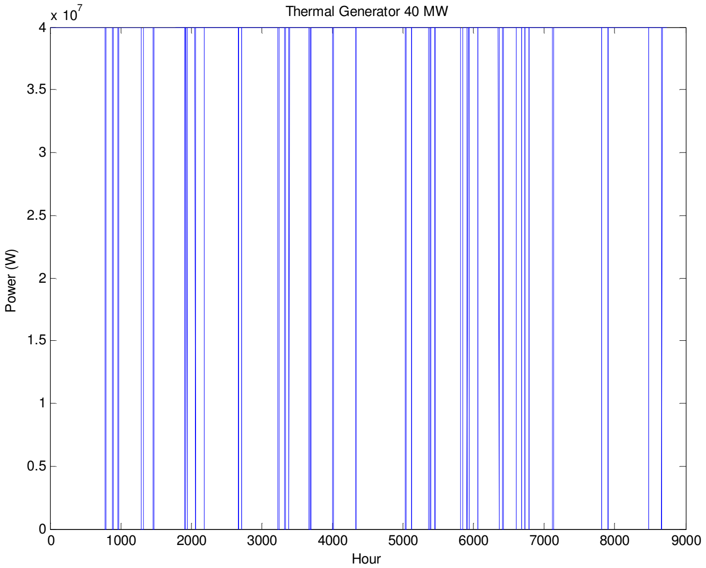
  Total CO2 emissions: 68048 tons/year



- Thermal generators of 40 MW (each)

  Total power along the year: 338.88 GWh

  Total CO2 emissions: 135552 tons/year



Weibull Distribution

The other simulation is the Weibull distribution for the wind. Each hour is assigned a value which changes every year. Thus the variability of the wind power can be simulated.

The variability of the wind speed simulated with the Weibull distribution makes it possible to simulate the output of a wind power farm.

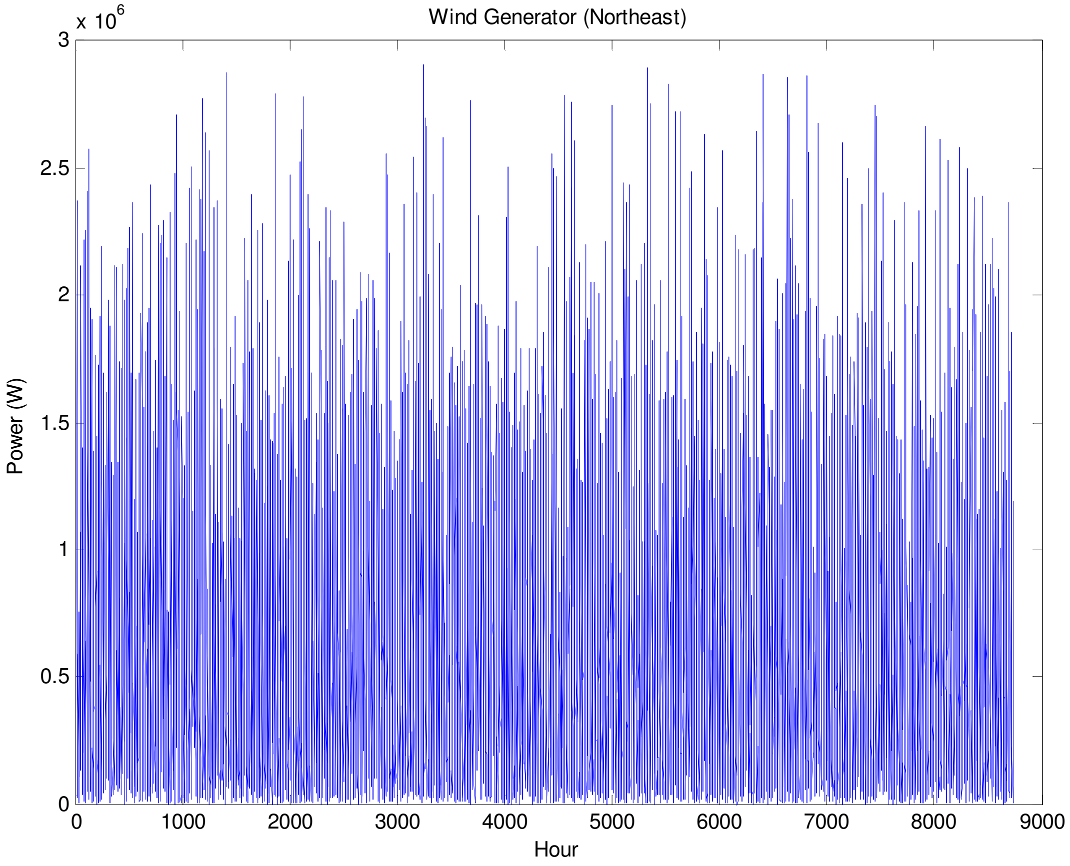
The following assumptions have been made in this work: the power generators of the wind system are always in the UP state, i.e. the variability of the wind power source is only due to the wind itself and not to whether the generator is working or not. Moreover, the transmission system is not taken into account, since the objective of this work is to assess the impact of the power plant positioning, while maintaining the same situation of distribution.

The simulation of one year of the wind power generator is shown as follows.

- Wind generator of 3 MW (based on the Northeast)

  Total power along the year: 4.82 GWh

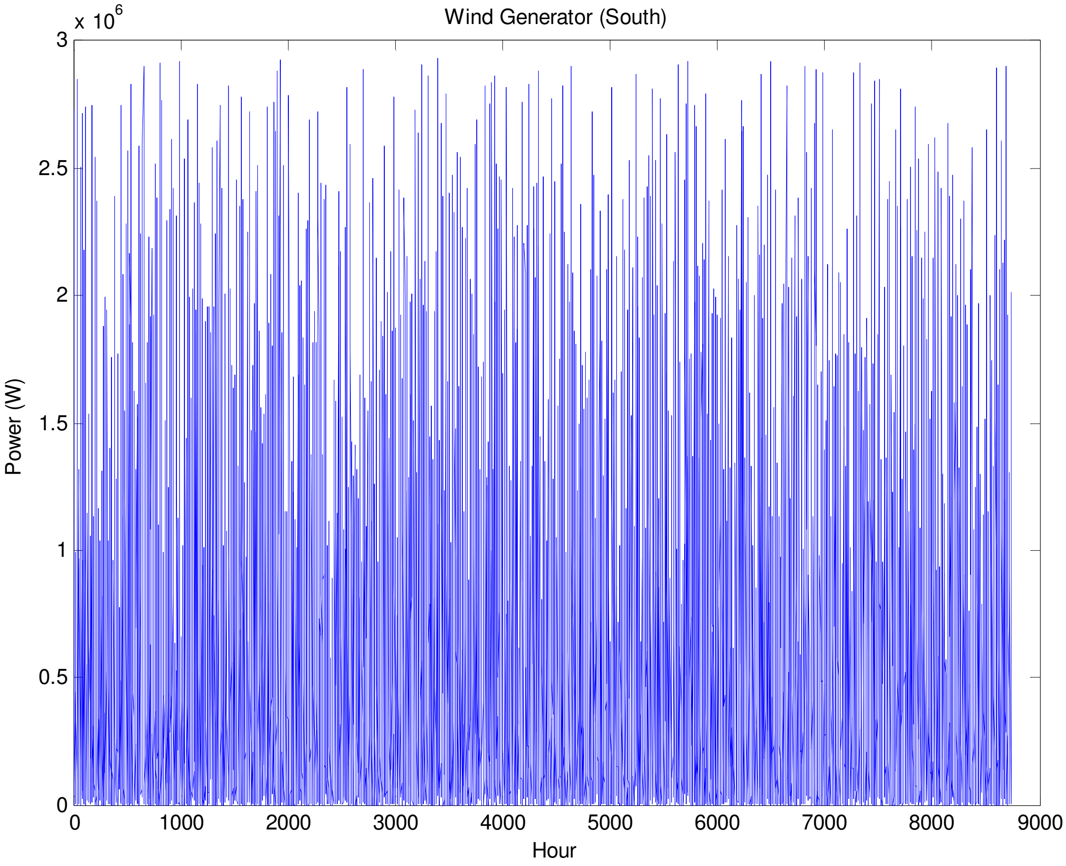
  Total CO2 emissions: 48 tons/year



- Wind generator of 3 MW (based on the South)

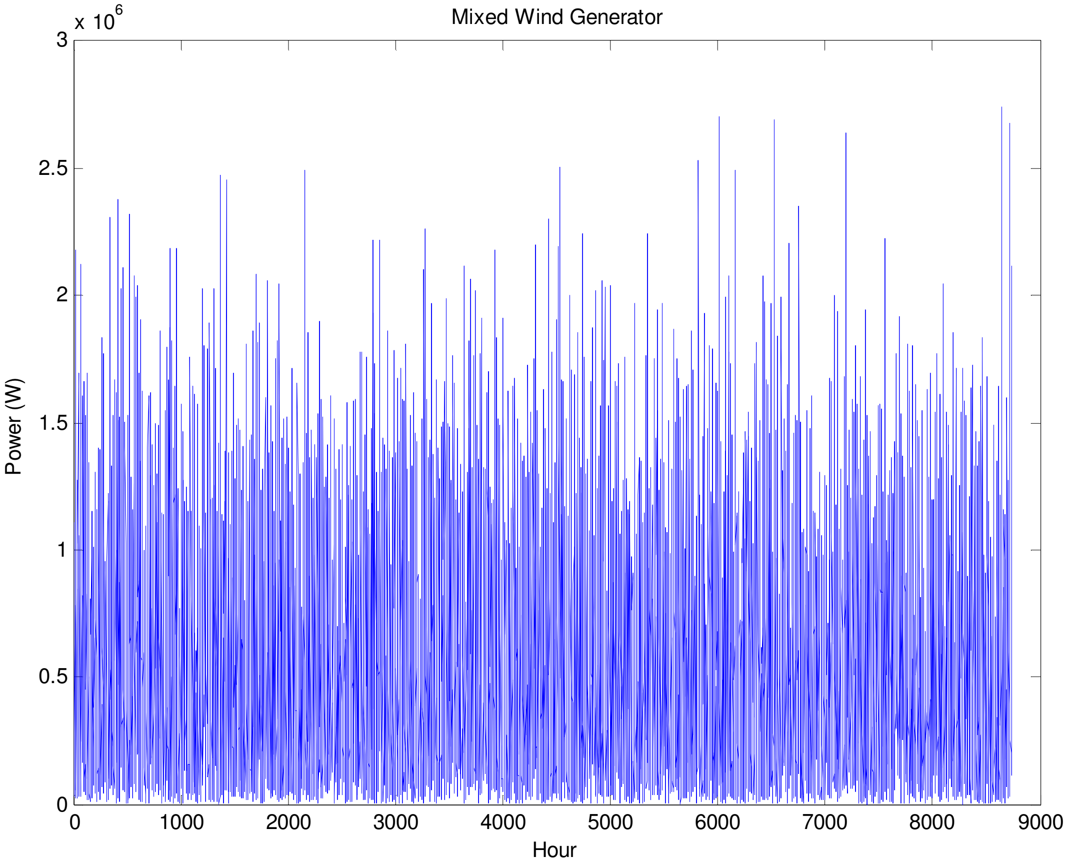
  Total power along the year: 4.08 GWh

  Total CO2 emissions: 40 tons/year



Simulating the operation of two generators of 1.5 MW, each of them located in one of the studied places (one in the northeast and other in the south). The results are:

- Two wind generators of 1.5 MW (one in the south one in the northeast)
  Total power along the year: 4.47 GWh
  Total CO2 emissions: 44 tons/year



This last scenario will be crucial to this work. Though having a smaller annual production, its implementation into a grid of power plants would be ideal, as far as reliability is concerned, which is what this work attempts to demonstrate.

Here the difference from the usual power in the behavior becomes evident. Following the wind speed distribution over the year instead of the two stages situation.

Another important fact is the difference between the amount of CO2 released into the atmosphere during the year compared to the Thermal system with two of the clean energy systems (hydro and wind)

9. Results

For the final system some cases are going to be studied. The objective here is to calculate the relation between the loss of energy expectation, loss of load expectation and the emissions of CO2. For each case the total emissions, the LOEE, the LOLE are going to be calculated and in the end compared.

This simulation is performed (alongside with other simulations) for a number of years until a stop criterion is found. In this work, the stop criterion is measured as the difference on the number simulated (in this case the reliability formulas) from one year to another. And when this difference is lower than 0,05% the simulation converges to the number showed.

In this work the wind farm is represented by the amount of 10 wind turbines each of them with the rated power of 3 MW. For simulating the division between the northeast and the south each farm is done with 5 wind turbines, to keep the maximum rated power and by this being able to compare the situations.

The first series of tests are going to try to prove the relationship between the reliability coefficients and the position of the wind farms. For this, some cases are going to be created variating the peak load, the increase of plants, the type of the new plants and the position of the wind farms.

The table bellow shows the cases studied.

Table 4 – Cases studied

Case	Peak Load (MW)	Increase of Load (MW)	Type of increase	Position of the wind farm
1	185	0	-	-
2	185	30	Thermal	-
3	185	30	Wind	Northeast
4	185	30	Wind	South
5	185	30	Wind	South (50%) + Northeast (50%)
6	215	0	-	-
7	215	30	Thermal	-
8	215	30	Wind	Northeast
9	215	30	Wind	South
10	215	30	Wind	South (50%) + Northeast (50%)

Reliability results

The simulation was made for each of the cases trying to prove the best position of the wind farms.

Table 5 – Reliability Results

Case	LOLE (hr/yr)	LOEE (MW/yr)	CO2 (tons/yr)
1	1.17	3.01	0
2	0.05	0.20	102.990
3	0.80	2.82	440
4	0.74	2.62	480
5	**0.58**	**1.58**	**500**
6	12.17	7.53	0
7	1.15	3.63	103.045
8	7.46	8.12	445
9	8.56	7.88	483
10	**7.31**	**8.08**	490

*Is measured the increase of CO2 emmisions in relation to the original system

By the table it's possible to note that the best situation using the wind farms are obtained when those farms are positioned in different places. This can be explained by the fact that the wind on those two places is not correlated, and this reflects on the amount of energy produced. On the other hand it's evident that the best solution by the reliability point of view would be the thermal power plant with the generation capacity equal to the total rated power of the farms. But, at the same time, the emmited CO2 in this situation is about 100 times the emissions with the wind farms.

The next simulation is done to see the "envorimental costs" of the increase of reliability i.e. the amount of CO2 emmited for different combinations of power plants thermal based and wind farms.

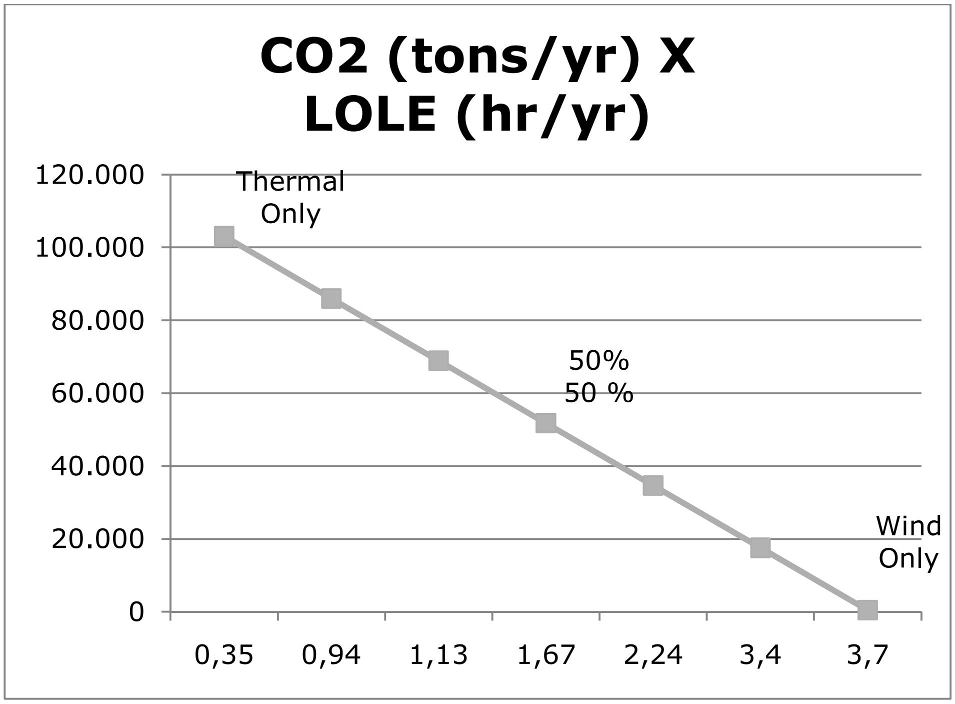
Reliability X CO2

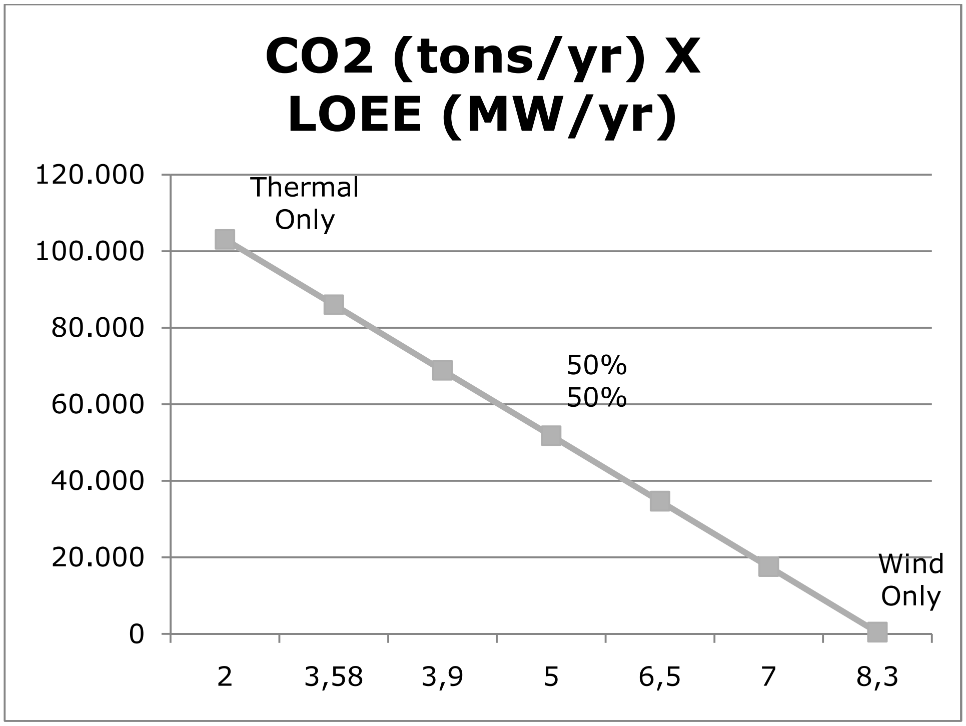
Here the simulations are done with the best reliability distribution from the table before (50% of the turbines in the south and the other 50% in the northeast). And the total increase of the base system is always 30 MW. The peak load used here was 210 MW.

Table 6 – Results

Wind (MW)	Thermal (MW)	LOEE (MW/year)	LOLE (hr/year)	CO2* (tons/year)
0	**30**	2	0,35	103.104
5	**25**	3,58	0,94	85.995
10	**20**	3,9	1,13	68.886
15	**15**	5	1,67	51.777
20	**10**	6,5	2,24	34.668
25	**5**	7	3,4	17.559
30	**0**	8,3	3,7	450

*Is measured the increase of CO2 emmisions in relation to the original system





It is obvious that using the thermal generators the reliability is going to be bigger than with the wind generators but the environmental cost of this improvement in the reliability would be too big.

10. Conclusion

As shown in the graphics, the reliability measures decrease with the mix of wind sources of different places. Considering that the wind speed in north and south Brazil is not correlated, this conclusion was expected.

Surprisingly, though the south location had worst wind conditions and Weibull factor, the same number of turbines combined can be better than only in the northeast. The expectation here was to the combined number of turbines with the same annual production would have this improvement. The results are even better though, and the same potential could turn into a more reliable system.

It was not possible to achieve the same degree of reliability offered by conventional energy sources by only making use of wind. The main reason for that lies in the fact that thermal systems, for example, enable to control the electricity output by simply managing the amount of fuel that is burnt, whereas the wind source is not controllable at all.

Further studies could be carried out on how to introduce more reliability measures so as to determine whether this conclusion applies to other situations; new power sources, such as solar, and try to find uncorrelated places and events to improve even more the reliability; consider a more complex system, the transmission system, power generators working in a lower level (3-state); and many more.

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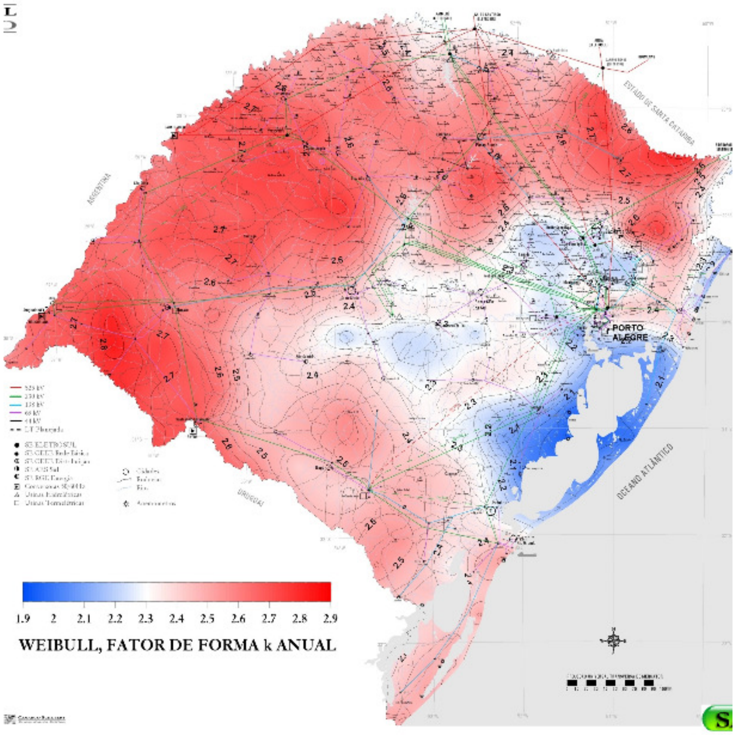
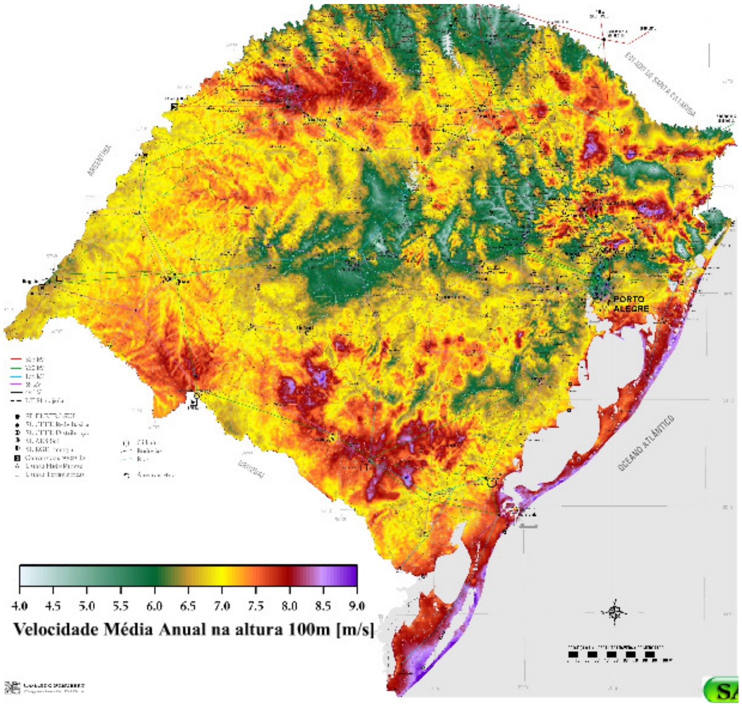
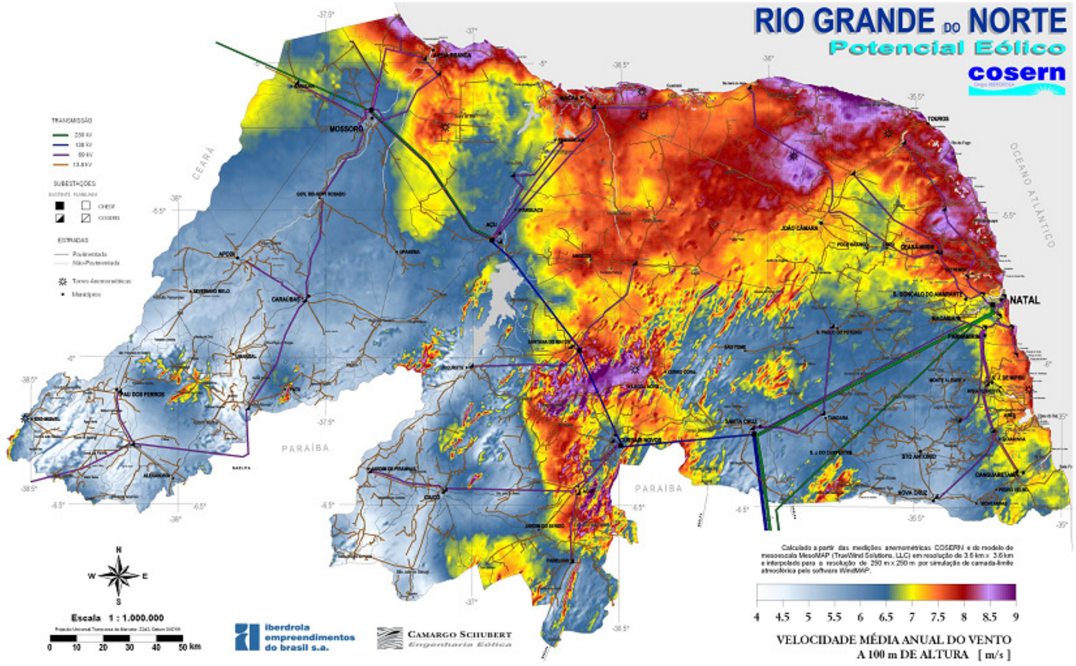
12. Append

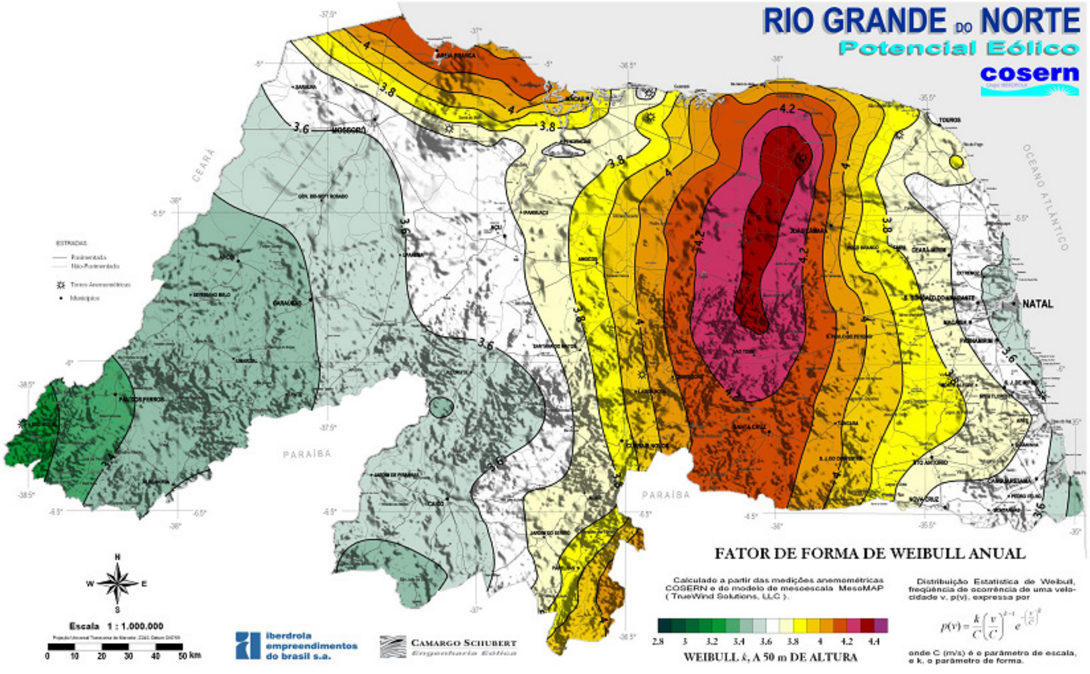
Weibull Distributions in Brazil







POTENCIAL EÓLICO A 100 METROS DE ALTURA



FATOR DE FORMA DE WEIBULL ANUAL

MatLab Programs

Model of the turbine:

```
vci = 3; % cutin speed
vr = 14; %rated speed
vco = 25; % cutout speed
pr = 3E6; %rated power
a = pr/(vr^3 - vci^3);
b = vci^3/(vr^3 - vci^3);
A = 1;
ni = 0.98;

v1=0:0.1:30
for i = 1:1:301
if v1(i) <= vci
         pw1 (i) = 0;
elseif      v1(i) <= vr
            pw1(i) = a*v1(i)^3 - b*pr;
elseif      v1(i) <= vco
            pw1(i) = pr;
else        pw1(i) = 0;
end
pout1(i) = pw1(i)*A*ni;
end
```

Markov

```
%Markov%
s(1) = 1;
lambda = 198 ;
mi = 2;

for i = 2:1:8700
    A = rand(1);
    if (s(i-1) == 1)
            if (A < (1/lambda))
                    s(i) = 0;
            else s(i) = 1;
            end
    elseif (A < (1/mi))
                    s(i) = 1;
            else s(i) = 0;
    end
end
```

Final program

```
%Monte Carlo Simulation Parameters

lambda = [198 198 196 157.6 157.6 157.6 157.6 195 147 194 194];
mi = [2 2 4 2.4 2.4 2.4 2.4 5 3 6 6];
ptot = [5 5 10 20 20 20 20  20 40 40 40]*1e6;
s(1,1:11) = 1;

n = 8736;   % The number of function evaluations
N = 10; %number of turbines

%Ini
load = PkWDH;
years = 1;
eps = 10;
lole(1) = 0;
LOEE(1) = 0;
%Variables
while eps > 0.003,
% Wind Weibull situations
LOLE1X = 0;
LOEE1 = 0;

% Northeast
shape1 = 4.4;
scale1 = 9.5/0.9;
x1 = scale1.*( -log(1-rand(n,1))).^(1/shape1);

%South
shape2 = 2.5;
scale2 = 8.5/0.88;
x2 = scale2.*( -log(1-rand(n,1))).^(1/shape2);


% Wind Turbine
po = 4000; % power required
vci = 3; % cutin speed
vr = 14; %rated speed
vco = 25; % cutout speed
pr = 3E6; %rated power
a = pr/(vr^3 - vci^3);
b = vci^3/(vr^3 - vci^3);
A = 1;
ni = 0.98;




% Power generated by the first turbine.
v1 = x1;
v2 = x2;


for i = 1:1:n
```

```
     for t = 1:1:11
    A = rand(1);
    if (s(i,t) == 1)
            if (A < (1/lambda(t)))
                    s(i+1,t) = 0;
            else s(i+1,t) = 1;
            end
    elseif (A < (1/mi(t)))
                    s(i+1,t) = 1;
            else s(i+1,t) = 0;
    end
    pout(t) = s(i,t)*ptot(t);
    end
    psaida(i) = sum(pout);


if v1(i) <= vci
         pw1 (i) = 0;
elseif      v1(i) <= vr
            pw1(i) = a*v1(i)^3 - b*pr;
elseif      v1(i) <= vco
            pw1(i) = pr;
else        pw1(i) = 0;
end
pout1(i) = pw1(i)*A*ni*N;


if v2(i) <= vci
         pw2 (i) = 0;
elseif      v2(i) <= vr
            pw2(i) = a*v2(i)^3 - b*pr;
elseif      v2(i) <= vco
            pw2(i) = pr;
else        pw2(i) = 0;
end
pout2(i) = pw2(i)*A*ni*N;

if load(i) > (pout1(i)+ pout2(i) + psaida(i))  LOLE1X = LOLE1X + 1;
    LOEE1 = load(i)- (pout1(i)+ pout2(i) + psaida(i));
end


end
%



    years = years + 1;
    lole1(years) = LOLE1X;
    LOEE(years) = LOEE1;
    avgloee1(years) = mean (LOEE);
    stdloee1(years) = std (LOEE);
```

```
    avglole1(years) = mean (lole1);
    stdlole1 (years) = std (lole1);
    eps = stdlole1(years)/sqrt(years)/avglole1(years);

end


years
avglole = mean (lole1)
stdlole = std (lole1)
avgloee = mean (LOEE)
stdloee = std (LOEE)
```