SYMBIOTIC COUPLING OF WIND POWER AND NUCLEAR POWER GENERATION

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ABSTRACT

The coupling of wind power production as an intermittent supply to nuclear power generation as a base load supply is discussed. Wind turbines on a standby operational mode are net importers of power for their control and yaw mechanisms. They need a supply of about 5 kW of power from an existing grid. They also require the vicinity of a power grid with excess capacity to export their generated power. A choice is the construction of wind farms in the immediate vicinity low population density population zones around nuclear power plants. An example is the Grand Ridge wind farm adjacent to the LaSalle nuclear power plant near Versailles, Illinois. Since the best wind resources in the USA are located far from the industrial and population centers there is a need for connection to the grid trough High Voltage Direct Current (HVDC). Due to ramping considerations, the planned introduction of 20 percent of electrical wind production in the USA by 2020 would pose challenging grid stability issues. Energy storage alternatives such as hydrogen production, compressed air, flywheels, superconducting magnets and pumped storage, need serious consideration.

1. INTRODUCTION

We consider the coupling between wind power and nuclear power and also discuss the integration of wind power through the use of high-voltage DC transmission lines (HVDC).
The Grand Ridge wind farm surrounds the site of the LaSalle Nuclear Power plant near Versailles, Illinois. The power station is operated the Exelon Power utility and consists of two Boiling Water Reactor (BWR) units supplied by the General
The wind farm covers an area of 6,000 acres around the LaSalle Nuclear Power plant in the Brookfield, Allen and Grand Rapids townships.

The project is welcomed by the local county boards. In addition to royalty and easements to land owners, each wind turbine is expected to generate $10,000 to $11,000 in property taxes annually, for a total of $660,000 to $700,000 - most of which will be distributed to local school districts. This is in addition to the rental fees of about $600 per month per turbine to the property owners.

Figure 1: Wind turbines rotor blades hauled around the LaSalle Boiling Water Reactor (BWR) near Versailles, Illinois.

Figure 2: Completed Grand Ridge wind farm around the LaSalle nuclear power plant uses General Electric (GE) wind turbines. The power station consists of two GE BWR units.

An expansion to Grand Ridge with a capacity of 111 MW is slated with an operational start in 2009. The Grand Ridge Wind Farm Project, eventually will encompass Phases I, II, and III to approximately 250 MW, consisting of the construction of up to 166 wind turbines, operation and maintenance (O&M)

building, project substation, approximately 1.5 mile generator lead line and collection system, and switchyard located in LaSalle County, Illinois. The total project area is 71,300 acres with the expected area of disturbance being approximately 175 acres.

The wind farm will eventually contain 500 to 600 of the GE-built, 1.5 megawatt turbines across the entire acreage. Invenergy has 14 wind farms either operational or under construction throughout the USA. Exelon Nuclear owns the transmission lines, which P.J.M. System operates. Invenergy sought and was granted permission to transmit electricity on the lines with excess capacity. Exelon will continue selling electricity to its customers in without change in the company's operating procedure. Invenergy, meanwhile, will sell electricity generated by the wind farm to the open market. At a cost of about \$140 million to \$150 million, the Invenergy project turbines have 262-foot tower and 143-foot blades. The turbines are spaced 2,500 feet apart, and will take about 40 acres of cropland out of production.

2. CAPACITY FACTOR IN ENERGY MIX

Substantial coal and nuclear energy is produced in the Eastern Interconnect in the USA, which includes the Midwest where Illinois is located. Hydro power is prolific in the Pacific Northwest, and a lot of energy also comes from natural gas. The energy contribution from renewable resources is small compared to the other generation types. In many states, the corresponding green circle in Fig. 3 is barely visible. California and Texas are two exceptions. However, the data is from 2006, and the capacity and energy from renewable resources in the system is steadily growing, aided by the fact that many states have established renewable energy standards.

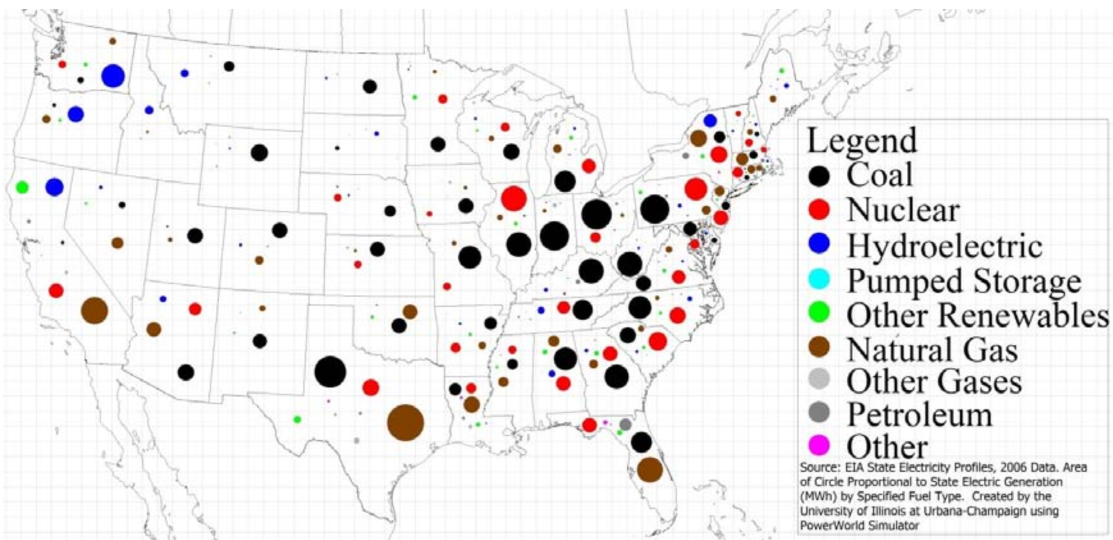


Figure 3. Electric Generation by Fuel and State. Figure: Kate Rogers.

Part of the reason the total energy produced from nuclear plants is so high is because they have a high capacity factor. The energy produced E in a year is:

$$E = 8760PC\ [MW.hr] \quad (1)$$

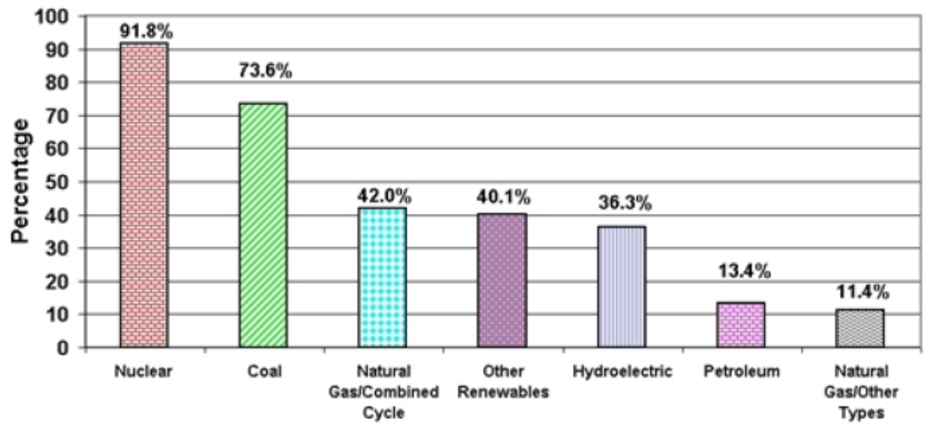
where: P is the rated power
C is capacity factor times
8760 is the number of hours per year.

A capacity factor of unity means that the plant would be operating at rated output all year. Nuclear plants come close to this with capacity factors above 90 percent.

There are currently 104 operating nuclear plants in the USA which had a combined output of 806.2 billion kWh and an average capacity factor of 91.5% in 2008 [1]. Capacity factor is the ratio of the plant's actual energy to the energy that would be produced if the plant was operating at its rated output for the entire year.

In the USA, as of October 2009, 16 license applications have been submitted to the Nuclear Regulatory Commission (NRC) for up to 25 new reactors.

The average nuclear capacity factor of 91.5 percent is very high, which is favorable for a number of reasons. A high capacity factor means that the installed capacity is being more fully utilized. Comparatively, Photo Voltaic (PV) solar systems only have a capacity factor in the range of 20-30 percent, and wind is only slightly higher.



Source: Energy Information Administration, Form EIA-860, "Annual Electric Generator Report;" Form EIA-923, "Power Plant Operations Report."

Figure 4. Average Capacity Factor by Energy Source, 2007 [3].

Wind power is becoming an increasingly important resource as the search for sustainable and efficient energy alternatives progresses. Wind turbines take advantage of the power in the wind and extract a portion of this power with their blades and then convert the mechanical energy to electricity and send it into the grid. Wind turbines have the advantage of having no fuel costs. Of course, there must be a grid to send this power into, which is one of the key problems with wind power, since the windiest areas are generally located far away from load centers and so require a massive transmission infrastructure to be added in order to have the ability to export the harnessed wind power.

Because of the intermittence of the wind, utility wind turbines are continuous net importers of electricity on a standby basis to the level of about 5 kW to supply their control and yaw mechanisms. They become net exporters only when the wind blows, and consequently require the vicinity of a power grid with excess capacity.

The wind is an intermittent resource, and therefore is not dispatchable in the way that conventional generation is. Conventional sources of power generation such as those that rely on coal and natural gas are dispatchable in the sense that their outputs can be adjusted as needed to meet the load in the system. Wind does not have this flexibility. In general, generation sources vary in the way they respond to a need for an increase or decrease in output. Units have ramp rates, where a ramp rate is a certain amount of gradual change in power output that is possible within a given time period. Coal units take longer to respond, whereas natural gas units can respond quickly.

Nuclear plants are difficult to vary in this way since changing the reactor's power output requires inserting and removing fuel or control rods. Power output of the reactor is controlled by managing the neutron flux. Nuclear plants are base loaded units and they prefer to be run all the time.

Because of the reactor dead time originating from xenon builup after a reactor shutdown, nuclear reactors need about 24 hours for the xenon neutron absorber to decay to acceptable levels before being restarted. If taken out of service, they lose approximately $1.2 million per day of potentially produced electricity for a 1,000 MWe plant and 5 cents/kw.hr. Thus, other than the necessary planned maintenance, nuclear plants do not want to be shut off, and often nuclear plants have a negative Locational Marginal Price (LMP) resulting from the fact that they would rather pay than be shut off.

Some experts in the power industry believe that the intermittency of wind will need to be coupled with fast-acting generators such as natural gas generators. It is believed that nuclear power plants cannot respond fast enough to be synergistic with wind power, and that in fact the coexistence of the two types of generation in the system has the effect of making the power system harder to control so that the generation matches the demand. It is argued that while natural gas generators may be symbiotic with providing for the wind power fluctuations, nuclear has its own important role to play in providing necessary base generation at a high capacity factor for wind turbines on a standby waiting for favorable wind conditions.

3. NUCLEAR ENERGY STATUS

Operation of nuclear plants can require high capital costs and high spending at times [4]. Over a nuclear plant's lifetime, components require replacing. The steam generators of Pressurized Water Reactors (PWRs) are typically replaced once over the generator's life, and each PWR has two to four steam generators. Each steam generator costs $40 million to $50 million to replace. Reactor vessel heads, which cost $20 million or more, are also typically replaced as a precaution. These replacements make the system operate more safely and can improve reactor performance. Despite high costs for equipment such as steam generators and vessel heads, nuclear plants achieve sustained high levels of output and reliability which gives them a solid economic argument. On average in 2008, nuclear power plants had an average estimated production cost of 1.87 cents per kWh. When adjusted, this corresponds to a total operating cost of approximately 2.3 cents/kWh. This is quite low, and production costs have been stable at this level for a number of years. That is, the high efficiencies achieved offset the high spending. With these low incremental costs of electricity, nuclear plants could easily be the least costly source of future electricity supply [4].

Nuclear energy is unique in that it is the only major source of baseload generation that does not emit air pollutants or greenhouse gases. As more emphasis is placed on controlling emissions, the role of nuclear in the global energy infrastructure will become even more important. In 2008, operating nuclear plants prevented the emissions of almost 3 million tons of SO_2, 1 million tons of NOx, and 689 million tons of CO_2 emissions. This amount of CO_2 is equivalent to the annual emissions from 133 million passenger cars, and the entire USA has only 136 million registered passenger cars. These savings in emissions can also be passed along as savings to customers who would otherwise be paying CO_2 compliance costs.

While investing in renewable energy sources like wind and solar, it is important to also make sure to take advantage of nuclear power, which is the single largest contributor to emissions-free power. Nuclear energy currently produces 72 percent of America's emission-free electricity [[1]2]. Nuclear energy also uses the least land per unit of energy generated, so nuclear power plants are a way to reduce carbon emissions while using land efficiently. The USA Energy Information Administration says that 69 new reactors will be necessary by 2030 to meet the carbon-production provisions to the climate bill and that without this expansion, the costs of electricity, natural gas, and reduction of carbon emissions will rise significantly. This reinforces the need for the growth of the safe and clean nuclear energy industry.

As electricity demand continues to grow, more base loaded generating capacity is needed, and nuclear can help to meet this need. A poll in March 2009 indicates that 84 percent of Americans think nuclear energy is important for our energy future, and this increased public support is good. However, the process of licensing and building the first few new nuclear plants is expected to take approximately 9-10 years. The nuclear plants at future sites where site preparation has started this year are expected to begin commercial operation around 2016. The long time frames and high capital costs involved with construction are a drawback to building new nuclear plants, but the processes to get nuclear plants constructed and operating quickly and safely are constantly being improved.

At Pennsylvania-New Jersey-Maryland (PJM) Interconnection, who operates the transmission system for 51 million people, has 29 nuclear power plants on their system with a capacity of 30,500 MW [1]. These 29 nuclear plants supply about 35 pecent of the energy used in the PJM system. Coal and nuclear together comprise 59 percent of PJM's capacity, but they supply more than 90 percent of the energy in the system. Nuclear plants are baseloaded and run constantly, so the market price is generally set by more expensive units. The difference in market price and generation cost for nuclear plants helps nuclear plant operators economically operate their plants. Having a large, reliable, low-cost base of nuclear plants allows PJM to have available the other types of power sources which respond to the continuous fluctuations in daily energy demand [1].

China and India already recognize this importance of using nuclear power, alongside renewable, in meeting goals of greenhouse gas reduction. China is expected to build 40 new reactors by 2020 and India is expected to build 17. The SA, on the other hand, is expected to build four to eight by that time, and Britain and France will each build two. Major growth of the nuclear industry is also expected in Russia and Korea who are building 14 and 10 new reactors, respectively.

4. WIND POWER INTEGRATION CHALLENGES

Since the wind cannot be controlled, wind plants exhibit greater uncertainty and variability in their output compared with conventional generation. Power systems now already handle a large degree of uncertainty, which is mostly in the loads. In power systems, generation must always be equal to the load plus the losses. Demand is constantly matched with generation to maintain the system frequency of 60 Hz in the USA. However, the amount of uncertainty is increased with wind. Wind's variability and uncertainty have been shown to increase the operating costs for the non-wind portions of the system, but generally only by modest amounts [3]. A summary of the key insights on wind integration is provided in [3], accumulated from a number of wind integration studies conducted over the last several years:

1) Several investigations have been done with truly high (up to 25 prcent energy and 35 percent capacity) penetrations of wind and have concluded that power systems can handle such levels of penetration without compromising system operation.

2) The importance of detailed wind resource modeling has been clearly demonstrated. This modeling allows the ability to capture wind impacts, both for individual wind plants and among multiple wind plants in an area.

3) The value of good wind forecasting has been clearly demonstrated for reducing costs.

4) During light-load conditions (such as at night), it is more difficult to maintain system balance when levels of wind penetration are high. The solution to this problem will entail some combination of wind curtailment, wind ramp-rate mitigation, switching in more loads during light-loaded periods, and flexibility of the other generating units.

5) The need importance of the flexibility of the other generation sources in the mix has been made clear. The article suggests that such flexibility may come from sources such as high-ramp-rate fossil generators, hydro power, pumped storage, and demand response.

6) The value of sharing balancing functions over large regions which have a diversity of loads, generators, and wind resources has been clearly demonstrated. The electric power industry seems to be moving in this direction, which will significantly aid in the integration of large amounts of wind power by reducing operating costs associated with the variability of wind.

Some of the challenges with supporting increased penetration of intermittent resources are related to issues in the transmission system, distribution system, interconnection standards, operational issues, and forecasting and scheduling. Since good sites for wind are often in remote areas, planning for and executing transmission expansion is necessary to the growth of the wind sector. Furthermore, studies are needed to assess the regulation and ramping capacities of the generation mix. In regions with many thermal and nuclear plants, such ramping is not readily available [4]. This implies long-term resource adequacy issues which need to be addressed. Due to the steepness of the wind turbine power curve as illustrated in Fig. 5

below, a wind farm creates significant ramping needs as the wind speed changes.

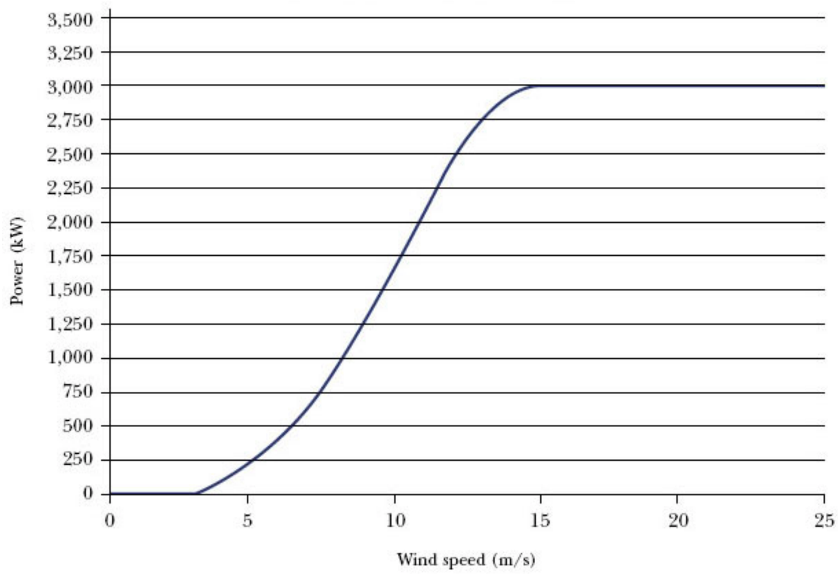


Figure 5. Wind Turbine Power Curve [4].

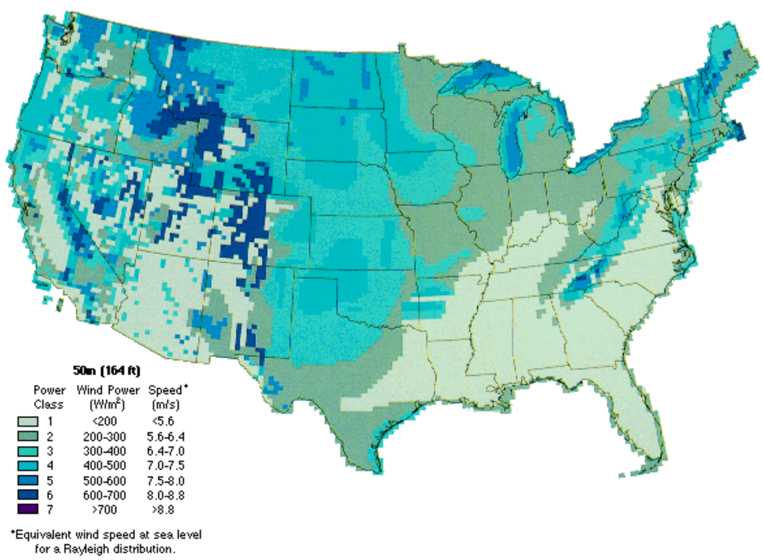


Figure 6. Wind energy resources in the USA are concentrated in the Rocky Mountain areas away from the industrial and population centers in the Midwest and East.

Then, at high wind speeds, when the turbine controls shut off the power generation to prevent damage due to over-speed and tensional oscillation, another operational challenge is posed to the system due to a steep reduction in generation levels. Another interesting challenge is that of storage. If the storage problem could be solved, that may solve some of the other major issues with wind power integration. The "must-take" policy of current power systems to wind and renewable resources can actually be considered a disincentive for wind farm operators and others to design a system to provide their own storage capability and energy balancing [4].

5. HIGH VOLTAGE DIRECT CURRENT (HVDC) TRANSMISSION

High voltage direct current (HVDC) is characterized by low losses and low capital cost for long transmission distances [5].

Above the critical length of about 600-800 km, HVDC becomes more economical, and the critical distance is even shorter for submarine cables [5]. Currently, about 70,000 MW of HVDC transmission capacity is installed in over 90 projects [5]. The development of HVDC technology started in the late 1920s, and the first commercially operating scheme was commissioned in 1954. In the 1990's HVDC technology performance was further enhanced as the converters improved. HVDC transmits power over long distances via overhead lines, submarine cables, or underground and offers a simple way to interconnect asynchronous grids. An HVDC technology which uses a voltage source converter (VSC) is known as HVDC Light and offers advantages for reliability and stability. AC transmission lines become inefficient at transmitting power over extremely long distances and as the lines get longer, less and less power can be transmitted without potentially making the system unstable.

HVDC Light technology allows simple control of voltages at the ends of the lines, and this is important since there is some question as to what wind farm operators are doing now to maintain their voltages at acceptable levels and whether they need to be doing more. HVDC Light technology could help put some of the significant voltage concerns to rest. The VSCs can also be useful in restoring the system following an outage or even a blackout. As an added benefit, with HVDC systems, power flow amount and direction can be easily controlled due to the power electronics converters located at both ends of the line.

Most AC lines do not have such controllers, although such technology does exist and has been well-developed, at least theoretically, since the 1980s. Flexible AC Transmission System (FACTS) devices [6] are controllers with the aim of providing flexible control of power system quantities such as voltages and real and reactive power flows. In fact, such FACTS devices could be extremely beneficial to increasing wind penetration by allowing better utilization of existing systems. An example of using FACTS devices to support wind penetration is taking place in windy West Texas [7]. Conventional FACTS devices are often prohibitively expensive and thus are limited to only one or two installations by a utility company in the system. Conversely, the recently-introduced D-FACTS devices are less costly and designed in a modular way so that they can easily be distributed to the most effective locations in the system where their use would produce the most benefit [8]. D-FACTS devices allow the effective impedance of transmission lines to be changed [9] and can thus be used to control power flow or to minimize losses [10].

6. SOUTHWEST POWER POOL (SPP) EXTRA HIGH VOLTAGE (EHV) OVERLAY PROJECT

The future will be driven by issues such as increased energy efficiency and demand-side management. Renewable energy resources such as wind can reduce dependence on fossil fuels as well as harmful emissions into the atmosphere. Wind energy technologies are well-developed and continue to be improved. For wind energy to achieve high levels of penetration and to achieve the desirable impacts on the environment, there are still many challenges to overcome. These challenges involve the integration of large amounts of wind power into the underlying systems which must support them.

The Southwest Power Pool (SPP) report [11] compares potential transmission expansion plans needed to support possible models of the future in the year 2026. The report includes the assumption that 15 percent of energy in the USA Eastern Interconnect in 2026 comes from renewable sources. This assumption reflects the idea that renewable energy sources will gradually be replacing polluting sources of energy such as coal. Of the 15 percent renewable energy considered in the study, 50% is assumed to come from wind power. The remaining additional generation is allocated as follows: 60 percent coal, 20 percent nuclear, and 20 percent gas. A high-nuclear generation future is also studied in the report in which the allocations are instead 40 percent coal, 40 percent nuclear, and 20 percent natural gas. In particular, 13,000 MW or more of wind power is modeled in the study, mostly in Oklahoma, Kansas, New Mexico, and the Texas panhandle. Other considerations in the project include renewed interest in nuclear power, load growth, expanding energy markets, and increased energy interchanges between areas and between grids.

In general, a high-voltage transmission system is required to support increased penetration of wind, and some of these transmission lines may be high-voltage DC lines for the reasons described earlier. The cost for different transmission options from [11] is given in Figure 7.

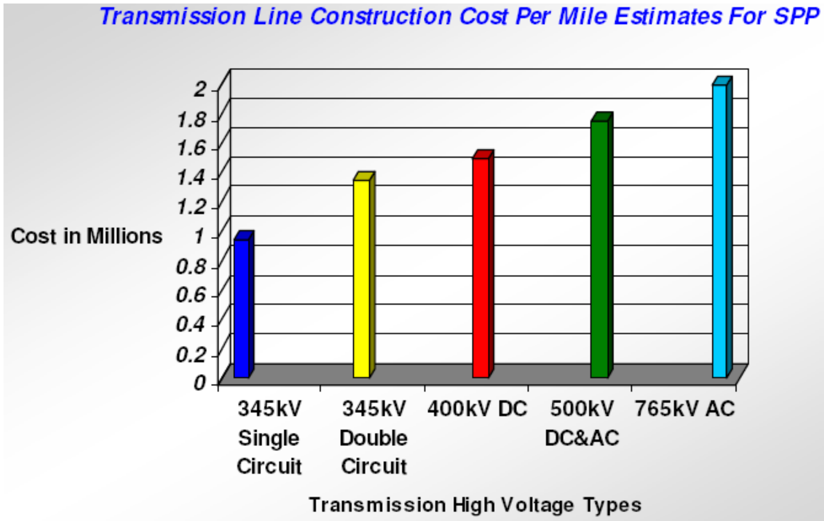


Figure 1. Extra High Voltage, EHV Transmission Cost Estimates from SPP Report [11].

Wind turbine generators are not located in close proximity to load centers, so efficient transmission is a necessity for massive wind power deployment to become a reality. The study develops five transmission alternatives and ranks the best alternatives. The transmission voltages studied include 345 kV, 500 kV, and 765 kV.

In all cases, the use of lower voltage lines, i.e. 345 kV, was found not to be realistic. Even if the use of lower voltage lines does not create higher costs and higher losses, the need for a larger number of lower voltage lines would require acquisition of all the necessary right-of-ways. The conclusions of the SPP report found the best-performing alternative to be a 765 kV plan. In general, in 2026, which is the study year, it is expected that the driving issues will be the following: increased energy efficiency, demand side management penetration, environmental issues such as the recently proposed carbon tax that will affect the existing and future generation fleet, and extensive demand for renewable energy in the USA electric system. These factors are expected to result in a massive increase in wind development, increased gas generation, renewed interest in nuclear power which may result in an expansion, increased interchanges of energy, and emerging and expanding energy markets [11].

From the SPP report, one can see that massive deployment of wind generation cannot happen without careful planning, and this includes upgrading the transmission infrastructure. The SPP report also identifies a need to explicitly study the issue of energy storage from the perspective of large wind farm operation.

7. WESTERN WIND AND SOLAR INTEGRATION STUDY

Work is in progress on the Western Wind and Solar Integration Study [12], [13]. Results so far show that there is significant variation of the wind both from year to year and from month to month. It is also clear that cooperation between balancing authorities is very important for high penetrations of wind, and that geographic diversity of wind helps mitigate variability. Wind often drops at night at the times when the load is increasing, and this effect can be extreme in summer evenings. In the spring, difficulties can ensue when the wind is strong and the load is low.

In some scenarios, wind helps the operator balance the system, but there are other times when the wind should be curtailed. The most concerning types of events are those where load is increasing while wind is dropping off; this motivates the consideration of interruptible loads or demand-side management. There is also some danger that too much wind would cause the nuclear units to try to cycle. Figure 8 shows the load during a windy study week in April for the study's basecase which includes no new renewables [13]. Nuclear and coal are baseloaded and running pretty much constantly whereas hydro units and combined cycle units are cycling with the daily load.

When the penetration of renewable is increased to 35 percent in the study [12], the combined cycle units are almost completely off, gas turbine output has increased, the coal plants are cycling significantly, and even the nuclear plants are cycling some as indicated in Figure 9. This is a problem and indicates that perhaps some of the wind generation should be spilled instead.

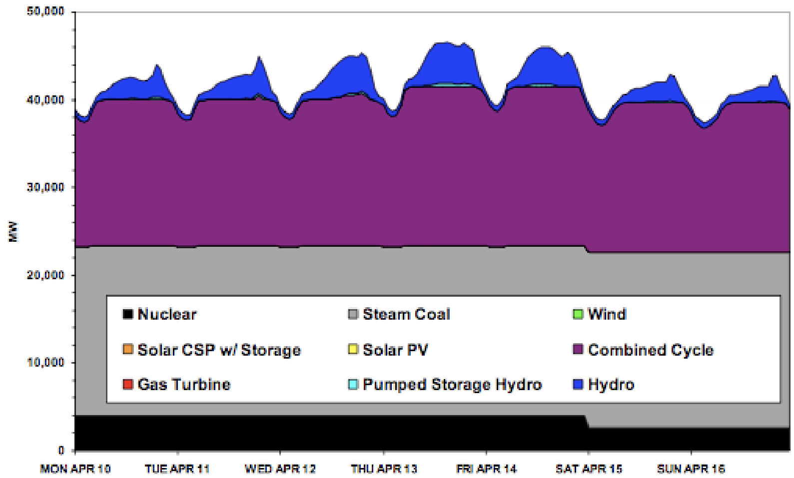


Figure 2. Load for the Western Wind Integration Study Base case - No New Renewables [12]

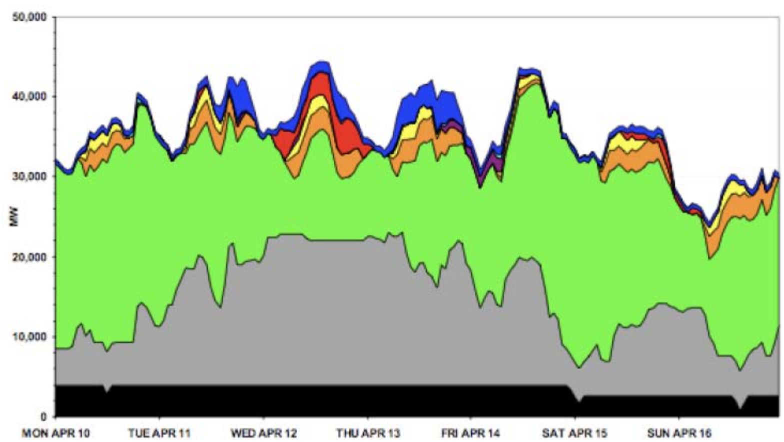


Figure 3. A week in April from the Western Wind Integration Study – 30 percent Renewables [12].

8. CONCLUSIONS

Wind and nuclear power both have their place in the coming emissions-sensitive energy environment. The technologies are opposite in many respects, but have in common the fact that they can provide the grid with low-cost energy without emitting greenhouse gases. It has been repeatedly shown that support for high penetration levels of wind power requires a vast high-voltage transmission infrastructure, as the best areas for wind are typically far away from load centers. It can also be seen that in this enhanced transmission system, High Voltage DC (HVDC) lines may have an important role to play since they have low losses and become economical for the required long stretches of new transmission lines. However, there is no easy solution. Nuclear power is excellent for providing base load power but does not really offer the flexibility to complement the fluctuations which are natural in wind power output. It is believed that such fluctuations must be matched with high ramp-rate units such as gas turbines which change their outputs quickly and easily. The solution is not black and white; it requires a broad insight into the different mix of resources, both generation and load, which may be available to the system both now and in the future.

Wind turbines on a standby operational mode are net importers of power for their control and yaw mechanisms. They need a supply of about 5 kW of power from an existing grid. They also require the vicinity of a power grid with excess capacity to export their generated power. Due to ramping considerations, the planned introduction of 20 percent of electrical wind production in the USA by 2020 would pose challenging grid stability issues. Energy storage alternatives such as hydrogen production, compressed air, flywheels, superconducting magnets and pumped storage need further consideration.

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