WIND POWER AND CO_2 EMISSIONS, by Willem Post, dated June 30, 2011

INTRODUCTION

The New England Electric Grid, NEEG, managed by ISO New England, ISO-NE, has a generating capacity of about 34,020 MW, electrical energy supplied to the grid is about 130,000 GWh/yr. It includes over 350 central power plants and 8,000 miles of high-voltage transmission lines to serve about 6.5 million customers. The supply to 2010 NEEG is 55.4% from CO_2-producing fossil fuels (44% gas, 11% coal, 0.4% oil), 29% from CO_2-free nuclear, 6.2% from CO_2-free hydro, 3.3% from interstate transfers, 3% from CO_2-producing wood waste, 2.4% from CO_2-producing solid waste and 0.7% from Other i.e., CO_2-free wind, solar, etc. Almost all of this energy is STEADY and the T&D systems of the NEEG are designed accordingly. http://www.iso-ne.com/nwsiss/grid_mkts/enrgy_srcs/index.html

Historically, electric grids have experienced varying electric demands during a day and varied the output of their generating plants to serve that demand and, at the same time, regulate frequency.

Cold, quick-starting, quick-ramping peaking plants, such as a mix of gas-fired OCGTs and CCGTs, are turned on and off each day to serve normal daily peak demands which occur once or twice per day. From a cold start, CCGTs take about an hour before there is enough steam pressure to operate the steam cycle. During this hour they run as OCGTs at about 30 to 35% efficiency, instead of the 55 to 59% efficiency as CCGTs. http://www.ge-flexibility.com/products/flexefficiency_50_combined_cycle_power_plant/index.jsp

Base-loaded coal and nuclear plants, which take about 6-12 hours from a cold start to rated output, are less suitable for variable output operation. Usually they operate near rated output for about a year for coal plants, for about 1.5 years for nuclear plants, after which they are shut down for 3-4 weeks for maintenance and refueling.

Base-loaded coal plants, designed for most economical, least polluting, steady operation near rated output, are often used to follow daily demand profiles and are sometimes used for the frequent, rapid cycling operations to accommodate wind energy; the coal plants used for suchcycling operations need to be designed for ramp rates of 5-10 MW/min for a 500 MW plant. http://www.repartners.org/pdf/coalwind.pdf

Cycling operations of coal plants require more fuel per kWh and emit more pollutants, including SOX, NOX, CO_2 and particulate per kWh, as shown by coal plants used for cycling in Colorado, Texas, etc. The main reason utilities use coal plants for cycling is because they lack sufficient capacity of hydro plants and gas-fired OCGT and CCGT plants to accommodate the mandated “must-take” wind energy. http://docs.wind-watch.org/BENTEK-How-Less-Became-More.pdf

Base-loaded nuclear plants, designed for most economical, steady operation near rated output, are very rarely used for cycling operations. They typically have capacity factors, CF, of 0.90 or greater.

Increased wind energy penetration will present additional challenges to grid managers, such as ISO-NE. Because wind energy is variable and intermittent, additional spinning, quick-ramping units, such as a mix of OCGTs and CCGTs, must be kept in 24/7/365 operation to supply and withdraw energy as required. The units must respond to changes of:

- demand of millions of users during a day.
- supply, such as from unscheduled plant outages.
- supply due to weather events, such as lightning, icing and winds knocking out power lines.
- supply from wind turbine facilities.

If these changes, especially those due to wind energy, are of high MW/min, the CCGTs may have to temporarily operate as OCGTs, because their heat recovery steam generators, HRSGs, would be damaged by the frequent, rapid, high amplitude cycling; HRSGs have lower ramp rates than OCGTs. This increased OCGT mode of operation increases fuel consumption, NOX and CO_2 emissions per kWh.

An example of what ISO-NE may have to look forward to: California’s wind and solar generating capacity will increase significantly in the near future largely due to government subsidies and “must-take” mandates. The management of their variable power on the grid is anticipated to be a significant grid operating challenge as:

- predicting day-ahead wind and solar outputs remains elusive, even with weather prediction systems
- sufficient cycling capacity of flexible generating units, such as OCGTs and CCGts, is not available at present
- the grid structure lacks the required transmission flexibility. http://integrating-renewables.org/grid-impacts/

The US Energy Information Administration projects levelized production costs (national averages, excluding subsidies) of NEW plants coming on line in 2016 as follows (2009$) :

Offshore wind $0.243/kWh, PV solar $0.211/kWh (higher in marginal solar areas, such as New England), Onshore wind $0.096/kWh (significantly higher in marginal wind areas with greater capital and O&M costs, such as on ridge lines in New England), Conventional coal (base-loaded) $0.095/kWh, Advanced CCGT (base-loaded) $0.0631/kWh. http://www.energytransition.msu.edu/documents/ipu_eia_electricity_generation_estimates_2011.pdf

SUMMARY OF STUDY RESULTS

Various aspects of wind energy on the NEEG, including capital costs, fuel requirements and CO_2 emissions reduction were studied. A comparison of the two alternatives was made. In this section are summarized the main results of the study.

Owning and O&M Costs of Wind Turbine Facility Plus Cycling Facility Versus CCGT Facility Plus Increased Energy Efficiency

Wind Turbine Facility Plus Cycling Facility

Wind turbine facility capital cost = 10,000 MW x $2,500,000/MW = $25 billion.
Wind turbine facility useful service life is about 20-25 years.
Wind turbine facility energy production = 10,000 MW x 8,760 hr/yr x CF 0.31 = 27,156 GWh/yr*

Cycling facility capital cost = 10,000 MW CCGT x $1,250,000/MW = $12.5 billion.
Cycling facility useful service life is about 30-35 years; short because of cycling.
Cycling facility energy production = 10,000 MW x 8,760 hr/yr x (1.0 - 0.31) = 60,444 GWh/yr
Cycling facility CO_2 emissions = 63,399 million lb of CO_2/yr.
Cycling Facility fuel costs = $2,167 million/yr
Extra annual costs for ISO-NE operating costs to deal with wind power.^

Capital cost of expanded overlay and T&D systems about $19 to $25 billion (source: NEWIS report)
Capital cost of expanded weather prediction facility.^
Capital costs of increased frequency regulation capacity.^

Annual owning and O&M costs of wind turbine facilities^
Annual owning and O&M costs of cycling facilities.^
Annual owning and O&M costs of expanded overlay grid and T&D systems.^

Annual owning and O&M costs of expanded weather prediction facility.^
Annual owning and O&M costs of increased frequency regulation capacity.^

Quality of life (noise, visuals, sociatal unrest/opposition), property value and environment are negatively impacted over a large area.

CCGT Facility Plus Increased Energy Efficiency

CCGT facility capacity = (27,156 +60,444) GWh/yr x 1,000 MW/GW)/(8,760 hr/yr) = 10,000 MW
CCGT facility capital cost = 10,000 MW x $1,250,000/MW = $12.5 billion.
CCGT facility useful service life is about 35-40 years.
CCGT facility energy production = 87,600 GWh/yr*
CCGT base-loaded CO_2 emissions = 64,779 million lb of CO_2/yr #
CCGT base-loaded fuel cost = $2,215 million/yr

Capital cost for expanded overlay grid and T&D systems: minimal compared to Alt. No. 1
Annual owning and O&M costs of CCGT facility: less than Alt. No. 1
Annual owning and O&M costs of built-out T&D systems: minimal compared to Alt. No. 1

Quality of life (noise, visuals, sociatal unrest/opposition), property value and environment impact: minimal compared to Alt. No. 1

* the CF gradually decreases as the facilities age.
# this reduction reduces the NEEG average of 1.0 lb of CO_2/kWh.
+ the cycling facility produces 60,444 GWh/yr of energy to balance 27,156 GWh/yr of wind energy; together they are seen by the grid as a base-loaded source.
^ not quantified in this study.

Note: The above production quantities require the capacities of the generation facilities of both alternatives to be about 5 to 10 percent greater to account for scheduled and unscheduled outages which will increase the above capital costs and owning and O&M costs.

Capital Cost	Alt. No. 1 $billion	Alt. No. 2 $billion
Wind facility	25.0	
Cycling Facility	12.5	
T&D build-out	19-25	
CCGT		12.5

Alt. No. 2 would produce (87,600/130,000) GWh/yr = 67.3% of the energy on the NEEG at a cost of about $0.0631/kWh, whereas Alt. No.1 would at about $0.10/kWh, or at about 58% greater cost, making New England less competitive in the US and the world.

Adding Alt. No. 2 to the existing low-cost, CO_2-free nuclear energy and the existing low-cost, CO_2-free hydro energy of Hydro-Quebec and New England, would place New England in a better competitive position versus the rest of the world than at present.

The fuel cost reduction is 2,215 - 2,167 = $47.2 million/yr, about 2% less than Alt. No. 2
The CO_2 emissions reduction is 64,779 - 63,399 = 1,380 million lb of CO_2/yr, about 2% less than Alt. No.2

The above indicates Alt. No. 2 (base-loaded/part-loaded CCGT facilities) requires much less capital cost, consumes slighly more fuel, emits slighly more CO_2, produces the same quantity of energy at a much lower cost/kWh and has almost no quality of life (noise, visuals, social unrest), property value and environment impact compared to Alt. No. 1 (wind facilities+cycling facilities).

The enormous capital cost difference could be much more effectively used for investments in increased energy efficiency which would more effectively reduce energy costs and CO_2 emissions per invested dollar.

http://www.coalitionforenergysolutions.org/renewables_are_expensive_an.pdf
http://theenergycollective.com/willem-post/47519/base-power-alternatives-replace-base-loaded-coal-plants
http://www.telegraph.co.uk/news/worldnews/europe/denmark/7996606/An-ill-wind-blows-for-Denmarks-green-energy-revolution.html

CO_2 Reduction Using OCGT, CCGT and Coal Plants for Cycling: PSCO of Colorado and ERCOT of Texas use a mix of OCGT, CCGT and coal plants for cycling which produces CO_2 emissions and other pollutants (SOX, NOX, particulate) that are significantly greater/kWh than without cycling, because the coal plant combustion systems and air quality control systems become unstable; they are highly unsuitable for frequent, rapid cycling. See Bentek study below.

A better approach would be for PSCO and ERCOT to retire older coal plants that have efficiencies of about 30% and emit at least 2.15 lb of CO_2/kWh and replace them with utility-owned, gas-fired CCGTs that have efficiencies of up to 60% and emit about 0.67 lb of CO_2/kWh. The CCGTs have short installation periods and capital costs of about 1,250/kW. With wind energy absent, this measure would reduce the most CO_2/kWh at the least $/kWh and would produce power at the least $/kWh.
http://theenergycollective.com/willem-post/59747/ge-flexefficiency-50-ccgt-facilities-and-wind-turbine-facilities

Wind Energy Accommodation Fees: nationwide wind energy accommodation fees vary from about $2/MWh at low wind energy penetrations to $9/MWh at high wind energy penetrations. Currently, the Bonneville Power Authority charges about $5.7/MWh, or $0.0057/kWh, for cycling its hydro plants to accommodate wind energy. Hydro-Quebec likely would charge a similar fee. http://www.lawofrenewableenergy.com/2009/07/articles/bpa-issues-decision-on-wind-integration-charge-in-2010-rate-case/

Some extra owning and O&M costs due to adding wind energy to the NEEG are:

- utility-owned cycling facility shorter useful service life due to cycling and extra O&M costs due to cycling
- expanded overlay grid and T&D systems
- expanded weather prediction systems
- increased frequency regulation
- additional ISO-NE management efforts

These extra owning and O&M costs would be significant. What percentage of those costs should be charged as wind energy accommodation fees to wind turbine facility owners?

Making Wind Facilities More Grid-Friendly

- owners of wind turbine facilities could minimize the wind power accommodation fees by installing their own cycling facilities to provide cycling energy BEFORE the wind energy enters the grid.

- wind turbine facilities could be designed to present less variable output to the grid, such as by automatically feathering their rotor blades to limit minute-by-minute ramp rates of their output, at minor reductions of production and at minor additions to capital costs. Ireland enacted a new grid code in 2004 that requires wind turbine facilities to reduce the variability of their outputs, i.e., be grid-friendly. See Page 17 of http://www.ref.org.uk/attachments/article/171/david.white.wind.co2.saving.12.04.pdf

Independent Power Producers and Power Purchase Agreements: Independent power producers, IPPs, usually sell their energy to public utilities under long-term power purchase agreements, PPAs. The IPPs have greater profits, if they operate their plants steadily near rated output. They do not make their plants available for cycling, as it would reduce their output and profits. Accordingly, only utility-owned plants are available for cycling. Public utilities operate on a cost-plus basis; their justifiable costs due to cycling would be made up with rate increases, or a fee on wind turbine facility owners, or both.

The IPPs of existing wind turbine facilities on the NEEG have PPAs with utilities. These IPPs have their facilities, capacity about 250 MW primarily in western Maine, in the best wind locations and have been getting a free ride as their wind energy impact on NEEG regulation and spinning plant operations is not yet “noticeable”, according to ISO-NE personnel. The main reason it is not noticeable is because of a lack of proper data measuring and recording.

As NEEG wind energy penetration increases, the impact would be noticeable and stricter requirements regarding frequency regulation and variability of wind turbine facility outputs would be required, instead of placing the onus on ISO-NE, NEEG plants and ultimately rate payers. Compliance with such stricter requirements is being deployed in nations with higher wind penetration, such as Spain, Ireland, Germany, etc. http://www.renewableenergyworld.com/rea/news/article/2010/10/how-spain-dealt-with-lvrt-problems

Collecting Power Plant and Grid Operating Data: ISO-NE would be well advised to set up centralized data logging at one-minute intervals of:

- electrical energy fed into and taken from the NEEG by all wind turbine facilities
- fuel consumption and CO2 emissions of all plants on the NEEG; many NEEG plants already report hour-to-hour emissions of NOX, SOX and particulate to the US-EPA.

Such one-minute data is essential for any accurate analysis and comparison of power generation alternatives to reduce CO2 emissions; flying blind regarding global warming is inexcusable and likely wasteful. The Electric Reliability Council of Texas, ERCOT, collects such data at 15-minute intervals.

STUDY PURPOSE AND APPROACH

The purpose and approach of this study is to:

- compare the owning and O&M costs of wind turbine facilities plus cycling facilities versus CCGT facilities only.
- determine the capacity of the cycling facility required to accommodate any wind energy changes.
- determine the impacts of several small, medium and large wind energy decreases.
- determine wind energy accommodation fees
- summarize the Bentek study “How Less Became More” regarding using coal plants to accommodate wind energy in Colorado and Texas.

http://docs.wind-watch.org/BENTEK-How-Less-Became-More.pdf

CYCLING FACILITY FOR ACCOMMODATING WIND ENERGY

The two main ways of economically accommodating wind energy are hydro power facilities and gas turbine facilities. Spain and Portugal use both, Denmark and the Bonneville Power Authority use hydro. See below website.
http://theenergycollective.com/willem-post/46977/impacts-variable-intermittent-power-grids

Two examples of cycling facilites to accommodate wind energy are described:

Denmark and Hydro Power

Denmark’s wind power operations is used as an example to learn from. Denmark’s prevailing winds are from the North Sea, across Denmark, to the Baltic Sea. The best winds are on Denmark’s northwest coast. Denmark has more than 4,000 onshore wind turbines with a capacity of about 3,150 MW, nearly unchanged since the end of 2003; the increases in capacity in 2009 and 2010 are due to offshore wind turbines. About 90% of the wind turbines are supplied by Vestas, a Danish company.

If the wind blows strongly in Denmark, and as the marginal cost of operating wind turbines is minor (i.e., ignoring major costs, such as for capital and O&M), there is a big incentive to maximize wind power output even if it is not needed by Denmark; the solution to avoid congestion on Denmark’s grids is to send the excess output to the much larger grids of Norway and Sweden. http://en.wikipedia.org/wiki/Hydroelectricity#Pumped-storage

Studies of grid operating data show that Denmark exports power to Norway and Sweden, and that those exports are highest during strong wind periods. Norway and Sweden have significant hydro plant capacity, including some pumped storage. The plants could be cycled at 100 %/min; if a burst of Danish wind energy arrives, the hydro plants reduce their own outputs to accommodate it.

However, sometimes Norway and Sweden do not take all of the Danish wind energy offered because reservoirs are already full, or are going to be full due to snow and rain fall, etc. In that case, grid operators direct utilities to reduce the output of a percentage of their wind turbines (by feathering the blades or stopping them), according to pre-planned sequences. This MO is much easier than requiring hundreds of small combined heating and power, CHP, plants or a few big central power plants to reduce THEIR outputs. In case of little snow and rain fall, hydro plant reservoir levels may be low and any wind energy from Denmark, if available, would be useful to conserve impounded water or to pump water from lower reservoirs to upper reservoirs.

This back-and-forth operation is inefficient and uneconomical, as various studies have shown. One indication of this inefficiency: Denmark has the highest residential electric rates in Europe, whereas its commercial rates are kept at about one third of the residential rates for international competitive reasons. France, 80% nuclear, has one of the lowest electric rates in Europe.

http://www.cedren.no/News/Article/tabid/3599/ArticleId/1079/could-Norway-be-Europe-s-green-battery.aspx
http://www.globaltransmission.info/archive.php?id=1424
http://www.cepos.dk/fileadmin/user_upload/Arkiv/PDF/Wind_energy_-_the_case_of_Denmark.pdf
http://theenergycollective.com/willem-post/46977/impacts-variable-intermittent-power-grids
http://theenergycollective.com/willem-post/51642/dutch-renewables-about-face-towards-nuclear
http://truenorthreports.com/uk-wind-power-not-making-the-grade

ISO-NE and Gas Turbine Cycling Facility

Because the NEEG has little hydro plant capacity connected to it, the least costly, least polluting, most suitable way of accommodating wind energy is not available to the ISO-NE.

Accordingly, the NEEG would need other, quick-starting, quick-ramping power plants for accommodating wind energy. The least costly, least polluting and most efficient power plants for this purpose are gas-fired OCGTs and CCGTs.

The US has a secure supply of natural gas for at least 100 years. The pollutants from natural gas are much less than from coal.

The US has a secure coal supply of at least 100 years. Coal gas used in up to 60% efficient CCGTs significantly reduces its adverse environmental impact versus using it in 35% efficient conventional gas plants.

THE WIND TURBINE FACILITY

Capacity, Production, Capacity Factor, Capital Cost and Location

A 10,000 MW wind turbine facility was chosen because the onshore wind power capacity of New England sites with Wind Class 3, 4, 5, 6, 7 winds is estimated at 10,989 MW. Wind Class 3 is usually considered adequate for community-scale wind facilities and Wind Classes 4 and greater are usually considered essential for utility-scale wind turbine facilities. See page 4 of http://www.iso-ne.com/committees/comm_wkgrps/othr/sas/mtrls/may212007/levitan_wind_study.pdf

If 10,000 MW of wind turbine facilities are implemented in the NEEG service area, the production would be 10,000 MW x 8,760 hrs/yr x New England average CF 0.31 = 27,156 GWh/yr, about 27,156/130.000 = 20.9% of current consumption.

A New England average CF = 0.31 was chosen because early installed wind turbine facilities would likely be on ridge lines with higher CFs, such as facilities in western Maine which have an average CF = 0.32, whereas later installed facilities would be on ridge lines with CFs of 0.30 or less.
http://www.coalitionforenergysolutions.org/maine_wind_farms.pdf

Some wind power proponents make optimistic statements regarding CFs calculated from wind speed measurements for a period of one to three years, but actual operating experience proves otherwise. The lower CFs are partially due to wind power curtailments to avoid excessive cycling stresses on the power plants connected to the grids, stresses on transmission systems and increased O&M downtime.

For example: In Denmark, the outputs of wind turbines are reduced to avoid excessive wind energy increases that would overwhelm Denmark's' small grid and that are not wanted by Norway, Sweden and Germany for various reasons.

The New England average CF = 0.31 may prove to be very optimistic, because large geographical areas rarely have capacity factors greater than 0.30. For comparison: Western Ireland (0.323 for the 2002-2009 period, the best in Europe, see website), UK (0.282 for 1998-2004), Texas (0.258 for 2009), Denmark (0.242 for the 2005-2009 period), the Netherlands (0.186), Germany (0.167). It would not be credible to aver onshore wind speeds in New England are comparable to onshore wind speeds in western Ireland, one of the windiest areas of Europe.
http://www.seai.ie/Renewables/Wind_Energy/Wind_Energy_Annual_Reports/2009_Wind_Energy_Annual_Report.pdf

Wind turbines require electrical energy to operate themselves, even when not operating. These energy requirements significantly increase to about 10 to 20% of a wind turbine's rated output during low-temperature winter conditions. http://www.aweo.org/windconsumption.html

The capital cost of the wind turbine facility would be 10,000 MW x $2,500,000/MW = $25 billion. An installed capital cost of $2,500,000/MW was chosen for this study. It is the same as the average of the capital costs of the recently installed operating and planned wind turbine facilities in Maine and less than the $2,778,000/MW of the Granite Reliable Power Windpark, Coos County, NH, consisting of 33 Vestas units @ 3 MW each.
http://www.coalitionforenergysolutions.org/maine_wind_farms.pdf

If the O&M costs of Kansas wind facilities is used as a base, then the O&M osts on ridge lines and offshore are about 2 and 3 times the O&M costs of Kansas, respectively. Kansas was chosen because it is flat and easily accessable for O&M, i.e., low owning costs/MW and low O&M costs/MW. It also has excellent winds, state average CF about 0.38.

As the ridge lines in New England have the best winds, it is assumed almost all wind turbines would be located on them. If the wind turbines are a 50/50 mix of 2.5 MW and 3 MW units, then about 10,000 MW/(0.5 x 2.5 + 0.5 x 3.0) MW = 3,636 units/(7 units per mile of ridge line) = 520 miles of ridge line would be required.

The wind turbines would be located in areas with the best winds, such as on the ridge lines of the north-south spine of Vermont, northern New Hampshire and western Maine; the latter two areas have greater average wind speeds than Vermont. With enough subsidies, even IPP-owned wind turbine facilities in Vermont will be profitable.

Such a concentration of wind turbine facilities would yield less of a reduction of wind energy variability normally associated with widespread geographic distribution of wind turbine facilities, i.e., the variability of wind energy would be reduced if some areas temporarily seeing higher wind speeds are combined with areas simultaneously seeing lower speed winds. Whereas this concept appears plausible in theory, in practice it has not been proven because typical weather systems extend 500 to 1,000 miles.

The 2.5 MW and 3 MW units are about 390 to 415 ft tall to the tip of the blade, respectively, which would appear very large if the ridge line is at 2,000 ft elevation and a person's house is at 1,000 ft elevation and within a mile of a row of wind turbines; at night there would be an unsteady beat of annoying/disturbing whoosh sounds. Wind turbines are often made to look small on distant ridge lines using Adobe's Photoshop software.

THE CYCLING FACILITY

Capacity, Production, Capital Cost and Location

The facility would produce 10,000 MW x 8,760 x (1.0 - 0.31) = 60,444 GWh/yr of wind balancing power, about 60,444/130,000 = 46.5% of current NEEG consumption, i.e., a major part of the NEEG power production would be by the cycling facility that operates at a significantly lower efficiency than it would operate at if wind energy were entirely absent. As a cycling facility, its CF is about 1.0 - 0.31 = 0.69, instead of 0.85-0.90, if it were base-loaded.

Such underutilization of a utility-owned asset has a significant owning and O&M costs of which a part should be added to the wind accommodation fees paid by wind turbine facility owners, NOT added to the electric rates of rate payers.

The cycling facility would be 10,000 MW x $1,250,000/MW = $12.5 billion, Any cycling facility must be utility-owned, not IPP-owned, to ensure it is available for cycling operations.

The cycling facility would be connected to the grid overlay to balance the wind energy BEFORE it enters the existing grids. If part of the cycling facility output is not needed for balancing, that part could be more efficiently operated in a base-loaded mode. If, for example, the overlay grid had 5 connection points to the existing grids, about 20% of the cycling facility could be located at each point. It would be somewhat similar to a highway encircling a large metropolitan area with connections to the existing roads systems.

A part of the cycling facilities could be located near the northern ridge lines and supplied with gas from Canada, and the rest of the cycling facilities could be located in southern New England and supplied with gas fron Pennsylvania. Most of the wind and cycling energy produced in northern New England would need to be transmitted to the people in southern New England.

T&D SYSTEMS AND GRID OVERLAY

At higher wind energy penetration percentages, most wind turbine facilities would need to feed into a transmission grid overlay which would be connected to the existing grids at several points that can accommodate the wind energy supply, as envisioned by several National Renewable Energy Laboratory studies.

The capital cost of the T&D systems would be $19 billion to $25 billion of new, highly-visible, transmission facilities. See below NREL reports.

The annual owning and O&M costs of the augmented T&D systems would be significant. Would owners of wind turbine facilities pay those additional costs as part of accommodating wind energy or will all this be placed under the heading of "smart grids"?

http://www.nrel.gov/wind/systemsintegration/pdfs/2010/ewits_final_report.pdf
http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf
http://www.boston.com/news/local/massachusetts/articles/2010/12/17/study_wind_could_be_fourth_of_new_englands_power/

INCREASED FREQUENCY REGULATING CAPACITY WITH INCREASED WIND ENERGY PENETRATION

Quick-ramping, spinning OCGT plants, diesel plants, pumped-hydro, run-of-river hydro, impounded hydro, large capacitors, flywheels, batteries, etc., are necessary to continuously maintain the 60 Hz frequency of the grid within a narrow band. The OCGTs in frequency-response mode, under nominal conditions, would run at reduced output to maintain a buffer of spare capacity and would continually alter their outputs on a second-to-second basis to maintain frequency with a so-called droop speed control.

When the demand exceeds the supply (including back-up spinning reserve), the voltage and frequency drop, which increases the loss-of-load-probability (LOLP). Even small changes in frequency or voltage (either positive or negative) can significantly increase the LOLP; loss of load implies blackouts and/or brownouts.

A demand increase, or a supply decrease, or both at the same time, would cause the generators on the grid to slow down. Their synchronizers would sense this and more steam or fuel is supplied to the steam or gas-turbine generators which would increase their RPMs. Some generators are slow to react, others are faster, such as spinning OCGTs, which would immediately ramp up until the others catch up.

Variable wind energy on the grid acts as a supply increaser and supply decreaser 24/7/365 in addition to normal demand and supply variations. Accordingly, greater regulating capacity is required with increased wind energy penetration.

With the current 0.5% of wind energy penetration on the NEEG, the hourly capacity used for frequency regulation varies from a low of 30 MW to a high of 200 MW , a 7:1 ratio. Over all hours of 2008, the weighted average hourly regulation, WAHR, was about 80 MW. The addition of wind power capacity would increase the real-time variability and short-term uncertainty of the electrical energy supply. See Page 171 of New England Wind Integration Study, NEWIS.

Based on a statistical analysis of ISO-NE grid operating data and on various other sources of wind data, the WAHR capacity would increase from the above about 80 MW with current wind energy, to a high of 315 MW at 20% wind energy penetration, 230 MW at 14%, 160 MW at 9% and 100 MW at 2.5%. See page 182 of NEWIS.

The WAHR values are AVERAGES. With 20% wind energy penetration and very large wind speed variations, as often happens in New England, the required frequency regulating capacity may be about 2,000 MW. http://www.beaconpower.com/files/ISO-NE-performance-paper-2010.pdf

The annual owning and O&M costs of operating a 4-fold increase in WAHR capacity would be significant. Would owners of wind turbine facilities pay those additional costs as part of accommodating wind energy?

INCREASED CYCLING CAPACITY WITH INCREASED WIND ENERGY PENETRATION

Normal Demand Following - Without Wind Energy

Quick-ramping OCGTs and CCGTs-in-OCGT-mode that normally provide power during peak demand hours of a typical day will have output variations as they ramp up and down to serve normal daily demand. A lesser capacity of OCGTs and CCGTs performs the same service during the other hours of the day.

The output variations are due to changes of:

- demand of millions of users during a day
- supply, such as from unscheduled plant outages
- supply due to weather events, such as lightning, icing and winds knocking out power lines

They can be positive or negative, they can be step changes or ramp changes. The smaller changes are smoothed by the inertia of the generators on the grid and by the spinning frequency regulating OCGTs. The larger changes require spinning OCGTs to frequently ramp or down as needed.

Because the normal daily demand profile from hour-to-hour and day-to-day is know with some certainty, any normal demand change is also known with some certainty and the appropriate intermediate and peaking plant capacity is deployed to service the changing demand.

Normal Demand Following - With Wind Energy

The magnitude and duration of large wind energy changes are not known with adequate and timely certainty, especially in an area with highly variable weather, such as New England.

Hundreds of weather stations all over New England, and beyond New England, would be required to monitor atmospheric conditions to predict, using computer programs, hourly forecasts of wind energy output for the next 48 hours, updated every 15 minutes, to be useful to grid operators for making day-ahead, unit-commitment decisions concerning which units to turn on and when to do so.

Such wind energy prediction systems are in operation with mixed success in nations with variable weather conditions, such as Denmark, Spain, Germany, England, Ireland, etc. http://docs.wind-watch.org/oswald-energy-policy-2008.pdf

The annual owning and O&M costs of such a weather forecasting facility would be significant. Would owners of wind turbine facilities pay those costs as part of accommodating wind energy?

Cycling Margins and Wind Energy Variations

Below are calculated the cycling margins required for predicted small, medium, large and very large wind energy variations.

With predicted weather conditions indicating small wind energy variations lasting less than 2 hours, about 40% of the cycling facility would be at about 50% of rated output so it could ramp up and down all times, the rest would be in production mode near rated output. Ramp up margin = 10,000 MW/2 x 0.40 x 0.50 x 2 hrs = 2,000 MWh.

With predicted weather conditions indicating medium wind energy variations lasting less than 3 hours, about 40% of the cycling facility would be in spinning mode (at about 0% of rated output), the rest would be at about 50% of rated output to be able to ramp up and ramp down as needed. Ramp up margin = 10,000 MW/2 x 0.40 x 3 hrs + 10,000 MW/2 x 0.60 x 0.50 x 3 hrs = 10,500 MWh.

With predicted weather conditions indicating large wind energy variations lasting less than 4 hours, about 60% of the cycling facility would need to be in spinning mode, the rest would be at about 25% of rated output. Ramp up margin = 10,000 MW/2 x 0.60 x 4 hrs + 10,000 MW/2 x 0.40 x 0.75 x 4 hrs = 18,000 MWh.

With predicted weather conditions indicating a significant weather front moving through New England with predicted wind speed decreases from about 35-40 mph to less than 7.8 mph lasting less than 6 hours, about 80% of the cycling facility would be in spinning mode, the rest would be at about 25% of rated output. Such a wind speed decrease may cause a wind facility output decrease from about 8,000 MW to 0 MW. Ramp up margin = 10,000 MW/2 x 0.80 x 6 hrs + 10,000 MW/2 x 0.20 x 0.75 x 6 hrs = 28,500 MWh.

Wind energy is produced irregularly during a year. For example:

- no wind energy is produced at wind speeds below 3.5 m/sec (7.8 mph) which occur about 10% of the time
- wind energy is produced at less than 10% of rated output about 30% of the time
- wind energy is produced at less than 31% of rated output (CF level) about 70% of the time
- wind energy is produced at greater than 31% about 30% of the time. Most of the larger amplitude cycling occurs during this period.

http://www.wind-watch.org/documents/analysis-of-uk-wind-power-generation-november-2008-to-december-2010/
http://docs.wind-watch.org/john-muir-trust-wind-report.pdf

Cycling to Accommodate Wind Energy

Wind energy is proportional to the cube of wind speed, a doubling of wind speed, which are frequently occurring events during a day, would increase wind energy 8-fold. Wind energy often varies by a factor of ten or more during an hour which is quite shock to the stability of electric grids if a cycling facility with adequate quick-ramping capacity is not available. In New England, such a wind event may occur when a rainstorm with lightning passes through. It starts with nearly no wind, then suddenly strong winds, much rain and lightning, and then almost no wind.

Adequate capacity of quick-ramping, spinning plants must be deployed, if the monitored atmospheric conditions give any indications of sudden, large wind energy changes; any such deployment must err on the safe side to avoid brownouts, etc.

If the cycling plants were to run out of ramping range, i.e., reach rated output, because wind energy decreased too much, then wind turbine output curtailment by feathering the rotor blades or stopping them (practiced in Denmark, Spain, Portugal, Germany, Texas, etc.) and demand curtailment by load-shedding would be required. http://www.masterresource.org/2011/04/renewable-lawsuit-colorado/

Less such cycling capacity would be required if energy could be drawn from and sent to other grids that are connected to the NEEG and if hydro plants, such as of Hydro-Quebec, HQ, would be available for cycling operations. However, the other grids and the HQ service area would likely have their own wind turbine facilities and may not have, nor be willing to share, spare capacity for NEEG cycling operations. Hence, the generating capacity of the NEEG would need to include sufficient quick-starting, quick-ramping plant capacity to provide energy when big decreases in wind energy occur. See Fig 1 of http://inside.mines.edu/~dkaffine/WINDEMISSIONS.pdf

Wind turbine facility IPPs could present a less variable output to the grid, such as by feathering their rotor blades and/or adding cycling plants consisting of diesel-generators or OCGTs to limit minute-by-minute ramp rates of the combined output. However, IPPs might object, as it would increase their owning and O&M costs; additional subsidies may be needed as an incentive.

Ireland enacted a new grid code in 2004 that requires wind turbine facilities to reduce the variability of their outputs, i.e., be more “grid-friendly.” See Page 17 of http://www.ref.org.uk/attachments/article/171/david.white.wind.co2.saving.12.04.pdf

Increased Cycling Energy With Increased Wind Energy Penetration

A spreadsheet for 0.5%, 1, 2, 3,....... to 20.9% wind energy penetration was prepared to illustrate the rapid decrease of available cycling energy and increase of wind energy accommodation costs with increasing wind energy penetration; the 0.5% corresponds to the about 239 MW of wind power capacity currently on the NEEG and the 20.9% corresponds to the 10,000 MW wind power capacity of this study.

Without Wind Energy: the energy supplied to the NEEG is about 130,000 GWh/yr of which about 54%, or 70,200 GWH/yr, is base-loaded (nuclear and coal; IPP-owned hydro and gas plants; Hydro-Quebec, etc. If about 30% x 130,000, or 39,000 GWh/yr, is supplied by utility-owned plants for intermediate and peaking energy to follow the daily demand, then about 16% x 130,000, or 20,800 GWH/yr, is non-base-load energy supplied by other IPP and utility-owned plants.

With Wind Energy: the energy supplied to the NEEG is about 130,000 GWh/yr of which about 54% + (wind + balancing)% is base-loaded, or 70,200 + 650 + 1,447 = 72,279 GWh/yr, at 0.5% wind energy penetration; wind energy plus balancing energy is equivalent to a base-loaded plant. Non-base-load energy is 130,000 - 72,279 = 57,703 GWh/yr, of which about 39,000 GWh/yr is required to follow daily demand, leaving 57,703 - 39,000 = 18,703 GWh/yr as non-base-load energy supplied by other plants. There must always be at least 39,000 GWh/yr, plus a margin in case of plant outages, of non-base-load energy for daily demand following.

The supply of utility-owned, base-loaded energy can be reduced (the IPPs are not interested in reducing THEIR outputs), and more (wind + balancing) energy can be added to the base-loaded portion until the utility-owned, base-load energy has been reduced to the safe/prudent lower plant operating limits. This means low-cost, base-loaded energy is replaced by high-cost, base-loaded energy which will increase electric rates.

Because the ISO-NE knows the exact ownership and capabilities of the 350 plants tied to the NEEG, it can quantify the available cycling energy to accommodate increasing percentages of wind energy penetration.

http://theenergycollective.com/willem-post/46977/impacts-variable-intermittent-power-grids
http://www.nrel.gov/docs/fy06osti/39524.pdf
http://www.fileden.com/files/2009/6/11/2474018/nofreewind/Cali-wind.jpg
https://wpweb2.tepper.cmu.edu/ceic/PDFS/CEIC_10_01_CWV.pdf
http://theenergycollective.com/willem-post/47519/base-power-alternatives-replace-base-loaded-coal-plants

NEEG System Conditions and Increased Wind Energy Penetration

Grids with a significant utility-owned OCGT and CCGT generating capacity, such as the NEEG, may have sufficient spare cycling capacity to accommodate up to about 1 to 2 percent of wind energy penetration. In New England, currently at about 0.5% penetration, its presence on the grid is not yet "noticeable”, according to ISO-NE personnel. The main reason it is not noticeable is because of a lack of proper data measuring and recording.

As wind energy penetration becomes larger, say 1%, wind energy variations will become noticeable, especially during unstable weather. At night, when demand is low, such capacity may already be available, but during daytime peak demand periods it will likely not be available.

Significant slow-ramping power generation capacity on the NEEG, such as nuclear and coal plants, cannot be used for cycling. Among the remaining generation capacity, only the part capable of quick-ramping could be used for cycling. Attempts in Colorado and Texas to use base-loaded coal plants for cycling proved less than satisfactory, especially during unstable weather. See Bentek report below.

IPPs in Maine are planning to install 2,000 MW of onshore wind turbines by 2015 which would result in about 4% wind energy penetration on the NEEG. However, the spreadsheet shows the spare cycling energy of the existing plants on the NEEG would allow only about 2 to 3 percent wind energy penetration.

This means NEEG utilities would need to install additional utility-owned OCGT and CCGT facilities and T&D systems to accommodate the wind energy of the 2,000 MW of wind turbines by 2015. The capital costs and the owning and O&M costs of the gas turbine facilities and T&D systems will ultimately result in significant additions to electric rates.

Wind turbine vendors, developers and financiers are aware of the near-term lack of spare cycling energy in the NEEG system and are rushing to get their projects built before it becomes common knowledge.

GAS TURBINE HEAT RATES

The gas turbines of the cycling facility, most efficient near rated output, would have to operate at a less efficient, more polluting, reduced output to be able to immediately vary their outputs to accommodate all variations of wind energy, including unpredictable, sudden, large variations of wind energy.

Gas turbine heat rates, Btu/kWh, and CO_2 emissions, lb of CO_2/kWh, increase because of increased inefficient operation below rated output of OCGTs, and CCGTs operating as OCGTs. For example: at 80, 50 and 20 percent of rated output, the heat rates are equal to the rated heat rate divided by 0.95, 0.85 and 0.55, respectively, or a heat rate degradation of (1/0.95 - 1) x 100 = 5.3%, 17.6%, and 81.8% respectively; CCGTs are rarely operated below 40% of rated output, because of much degraded heat rates.

This is for steady operation at a percentage of rated output. If the cycling facility is operating at a percentage of rated output AND irregularly and rapidly ramping up and down, the heat rate degradation increases further.

http://www.ge-mcs.com/download/bently-nevada-software/1q05_performancemonitoring.pdf
http://www.etsap.org/E-techDS/PDF/E02-gas_fired_power-GS-AD-gct.pdf

For example: a car driven on a level road at a steady speed of 40 mph has a mileage of, say 26 mpg. The same car driven on a level road at irregular and rapidly changing speeds that average 40 mph has a mileage of, say 22 mpg. The mileage degradation due to the speed changes would be (26-22)/26 x 100% = 15%. A car's best mileage usually is at 55 mph, at a steady speed, on a smooth and level road; it is the oft-quoted EPA highway mileage.

For this study it is assumed the heat rate degradation for:

- irregularly and rapidly ramping up and down is 0.90 for CCGT and 0.85 for OCGT operation
- reduced output is 0.90 for CCGT and 0.85 for OCGT operation

Heat rates and CO_2 emissions used for this study are:

Alt. No. 1: Irregular Ramping Up and Down Mode and Part-Loaded Mode

CCGT heat rate = (3,413 Btu/kWh/(eff 0.60 x cycling 0.90 x reduced output 0.90) = 7,023 Btu/kWh
CO_2 emissions/kWh = 117 lb of CO_2/(million Btu x 1 kWh/7,023 Btu) = 0.822 lb of CO_2/kWh

OCGT heat rate = (3,413 Btu/kWh)/eff 0.35 x cycling 0.85 x reduced output 0.85) = 13,497 Btu/kWh
CO_2 emissions/kWh = 117 lb of CO_2/(million Btu x 1 kWh/13,497 Btu) = 1.579 lb of CO_2/kWh

Alt. No. 2: Base-Loaded and Part-Loaded Mode

CCGT heat rate = (3,413 Btu/kWh/eff0.60 x reduced output 0.90) = 6,320 Btu/kWh
CO_2 emissions/kWh = 117 lb of CO_2/(million Btu x 1 kWh/6,320 Btu) = 0.739 lb of CO_2/kWh

OCGT heat rate = (3,413 Btu/kWh)/efficiency 0.35 x reduced output 0.85) = 11,472 Btu/kWh
CO_2 emissions/kWh = 117 lb of CO_2/(million Btu x 1 kWh/11,472 Btu) = 1.342 lb of CO_2/kWh

FUEL CONSUMPTION AND COST

Alt. No. 1, Wind + Cycling: Assuming an operating basis of 30% OCGT mode and 70% CCGT mode, the fuel cost of the cycling facility would be 60,444 GWh/yr x (0.30 x 11,472 + 0.70 x 6,320) Btu/kWh x $4/1,000,000 Btu = $2,167 million/yr

Alt. No. 2, CCGT Only: Assuming base-loaded and part-loaded mode, the fuel cost of the CCGT facility would be (27,156 + 60,444) GWh/yr x 6,320 Btu/kWh = $2,215 million/yr

The fuel cost reduction due to adding wind energy = 2,167 - 2,215 = $47 million/yr, about 2%

CO_2 EMISSIONS

Alt. No. 1, Wind + Cycling: Assuming an operating basis of 30% OCGT mode and 70% CCGT mode, the CO_2 emissions of the cycling facility would be 60,444 GWh/yr x (0.30 x 1.342 + 0.70 x 0.739) lb of CO_2/kWh = 63,399 million lb of CO_2/yr

Alt. No. 2, CCGT Only: Assuming base-loaded and part-loaded mode, the CO_2 emissions of the CCGT facility would be (27,156 + 60,444) GWh/yr x 0.739 lb of CO_2/kWh = 64,779 million lb of CO_2/yr

The CO_2 emission reduction due to adding wind energy = 64,779 - 63,399 = 1,380 million lb of CO_2/yr, about 2%

Note: the output variations could be monitored and recorded, at one-minute intervals, at the wind turbine facilities. The variations in fuel consumption could be monitored and recorded, at one-minute intervals, and correlated with other data to accurately determine the fuel consumption and CO_2 emissions to accommodate wind energy.

If a mix of OCGT, CCGT and coal plants were used, as in Colorado and Texas, the extra CO_2 emissions, and other pollutants, due to cycling would be significantly greater/kWh, because coal plants and their air quality control systems are highly unsuitable for frequent, rapid, larger-amplitude cycling. See Bentek study below.

WIND ENERGY ACCOMMODATION FEES

Nationwide wind energy accommodation fees vary from about $2/MWh at low wind energy penetrations to $9/MWh at high wind energy penetrations. Currently, the Bonneville Power Authority charges about $5.7/MWh, or $0.0057/kWh, for cycling its hydro plants to accommodate wind energy. Hydro-Quebec likely would charge a similar fee. http://www.lawofrenewableenergy.com/2009/07/articles/bpa-issues-decision-on-wind-integration-charge-in-2010-rate-case/

Some extra owning and O&M costs due to adding wind energy to the NEEG are:

- expanded utility-owned cycling facilities which will have shorter useful service lifes and extra O&M costs due to cycling hundreds of times a day to accommodate wind energy versus only a few times a day without wind energy.
- expanded overlay grid and T&D systems
- expanded weather prediction systems
- increased frequency regulation

- increased ISO-NE management efforts

The extra owning and O&M costs would be significant. What percentage of those costs should be charged as wind energy accommodation fees to wind turbine facility owners?

At current prices and future 20.9% wind energy penetration, the NEEG wind energy would have a wholesale value of about 27,156 GWh/yr x $0.0654/kWh = $1.776 billion and a retail value of about 27,156 GWh/yr x $0.14/kWh = $3.802 billion.

At current prices and current 0.5% wind energy penetration, the NEEG wind energy would have a wholesale value of about 650 GWh/yr x $0.0654/kWh = $43 million and a retail value of about 650 GWh/yr x $0.14/kWh = $91 million.

POWER PLANT CYCLING IN COLORADO AND TEXAS

Because the NEEG has very minor wind energy penetration, there would be no data to study fuel consumption and CO2 emissions related to cycling plants to accommodate wind energy, as there are in other jurisdictions. Accordingly, a recent study of Colorado and Texas, both states with significant wind turbine facilities, is used to illustrate some impacts of wind energy on plant operations.
http://docs.wind-watch.org/BENTEK-How-Less-Became-More.pdf

Power Plant Cycling In Colorado

Public Service of Colorado, PSCO, lacks sufficient gas-fired CCGT capacity for cycling to accommodate wind power. Instead, it is attempting to use coal plants for cycling for which they were not designed and for which they are highly unsuitable. The results have been significantly increased pollution and CO2 emissions per kWh.

The heat rate of a coal plant operated near rated output it is about 10,500 Btu/kWh for power delivered to the grid. It is lowest near rated output and highest at very low outputs. If a plant is ramped up and down (cycled) at a percent of rated output, its heat rate rises. See Pages 26, 28, 35, 41 of the Bentek study.

On Page 28, the top graph covering all PSCO coal plants shows small heat rate changes with wind power outputs during 2006. The bottom graph shows greater heat rate changes with wind power outputs during 2008, because during the 2006-2008 period 775 MW of wind facilities was added. For the individual PSCO plants doing most of the cycling, the heat rate changes are much higher.

On Page 26, during a coal plant ramp down of 30% from a steady operating state to comply with the state must-take mandate, the heat rate rose at much as 38%.

On Page 35, during coal and gas plant ramp downs, the Area Control Error, ACE, shows significant instability when wind power output increased from 200 to 800 MW in 3.5 hours and decreased to 200 MW during the next 1.5 hours. The design ramp rates, MW per minute, of some plants were exceeded.

On Page 41, during coal plant cycling across the PSCO system due to a wind event, emissions, reported to the EPA for every hour, showed increased emissions of 70,141 pounds of SOX (23% of total PSCO coal emissions); 72,658 pounds of NOX (27%) and 1,297 tons of CO2 (2%) than if the wind event had been absent.

Those increases of CO, CO2, NOX, SOX and particulate per kWh are due to instabilities of the combustion process during cycling; the combustion process can ramp up and down, but slowly. As the varying concentration of the constituents in the flue gases enter the air quality control system, it cannot vary its chemical stoichiometric ratios quickly enough to remove the SOX below EPA-required values. These instabilities persist well beyond each significant wind event.

PSCO does not release hourly wind power generation data. Such information is critical for any accurate analysis and comparison of alternatives to reduce such emissions; deliberately withholding such information is inexcusable.

Power Plant Cycling In Texas

The Texas grid in mostly independent from the rest of the US grids; the grid is operated by ERCOT. The grid has the following capacity mix: Gas 44,368 MW (58%), Coal 17,530 MW (23%), Wind 9,410 MW (12% - end 2009), Nuclear 5,091 MW (7%). Generation in 2009 was about 300 TWh. By fuel type: Coal 111.4 TWh, Gas CCGT 98.9 TWh, Gas OCGT 29.4 TWh, Nuclear 41.3 TWh, Wind 18.7 TWh. Summer peak of 63,400 MW is high due to air conditioning demand.

Wind provides 5 to 8% of the average generation overall, depending on the season. Its night contribution rises from 6% (summer) to 10% (spring). Texas capacity CF = 18.7 TWh/yr/{(9,410 + 7,118)/2) MW x 8,760 hr/yr)} = 0.258. Texas has excellent winds and should have a statewide CF of 0.30 or greater. Explanations for the low CF likely are:

- grid operator ERCOT requires significant curtailment of wind energy to stabilize the grid.
- vendors, developers and financiers of wind power facilities, eager to cash in on subsidies before deadlines, installed some wind turbine facilities before adequate transmission capacity was installed to transmit their wind output to urban areas.

Much of the gas-fired capacity consists of CCGTs that are owned by IPPs which sell their power to utilities under PPAs. That capacity is not utility-owned and therefore not available for cycling to accommodate the output of more than 10,000 MW of wind power facilities. Instead, utilities are attempting to use coal plants for cycling for which they were not designed. The results have been significantly increased pollution and CO2 emissions.

Unlike PSCO, ERCOT requires reporting of fuel consumption by fuel type and power generation by technology type every 15 minutes. The 2007, 2008, 2009 data shows rising amplitude and frequency of cycling operations as wind energy penetration increased. In 2009, the same coal plants were cycled up to 300 MW/cycle about 1,307 times (up from 779 in 2007) and more than 1,000 MW/cycle about 284 times (up from 63 in 2007). The only change? Increased wind energy penetration.

On Page 69: The ERCOT cycling of plants to accommodate wind energy produced results similar to the PSCO system; increased cycling resulted in significantly more SOX and NOX emissions than if wind energy had been absent. Any CO2 emission reductions were minimal at best, due to the significantly degraded heat rates of the cycling plants.

Remedy for Colorado and Texas Cycling Problems

A way out for PSCO and ERCOT is to retire older coal plants that have efficiencies of about 30% and emit about 2.15 lb of CO2/kWh and replace them with utility-owned, gas-fired CCGTs that have efficiencies of up to 60% and emit about 0.67 lb of CO2/kWh. The CCGTs have short installation periods and capital costs of about 1,250/kW.

If wind were entirely absent, this measure would reduce the most CO2/kWh at the least $/kWh and would produce power at the least $/kWh.

If some of the new units were cycled to accommodate wind energy, their Btu, NOX and CO2 per kWh would increase, mostly offsetting the CO2/kWh reduction due to wind energy, as shown by this and other studies.

In addition their operation as cyclers would incur an additional owning cost, because their CFs would be about 0.70, instead of about 0.85 - 0.90 as base-loaded units, as shown by this study and other studies.

http://theenergycollective.com/willem-post/47519/base-power-alternatives-replace-base-loaded-coal-plants
http://theenergycollective.com/willem-post/46977/impacts-variable-intermittent-power-grids