Operational Constraints and Economic Benefits of Wind-Hydro Hybrid Systems Analysis of Systems in the U.S./Canada and Russia

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Summary – Integrated operation of large-scale wind power plants with existing hydropower plants can provide significant technical and economic benefits for both technologies. In the United States, a study of the power system in the State of Vermont found that there are no major electrical system integration constraints to preclude wind power from becoming a large share of the state's generation system. Simulations showed that up to 810 MW of wind plants could be connected to the Vermont grid by 2010 without significant transmission and distribution system (T&D) upgrades or reinforcements. At that level, no congestion is expected to occur on main internal and external tie lines. Further, by integrating the potential wind power output from Vermont with the hydro-based system operated by Hydro-Québec in Canada, the value of wind could be up to 22% higher than sale at spot market prices, if the wind energy was exported during periods of peak demand in Québec, and if Vermont wind were perfectly correlated with Hydro-Québec load. In addition, the wind plants could also alleviate operating limitations and constraints on hydro plants located in cold climates by providing energy during winter when river flows are lowest, which is typically the windiest period and when power demand peaks. The wind-hydro concept that was modeled in detail for the US-Canada case, was also evaluated in Northwest Russia where the feasibility study for a 75 MW wind plant showed similar beneficial support for both seasonal and interannual hydropower plant operation and energy production as well as for water management. Overall it was concluded that wind plants could provide support for hydro plants and vice versa

Background

There is an increasing recognition of benefits from the synergy of wind-hydro, especially in cold weather climates, but little analysis has been performed to quantify the extent of these benefits. In addition, each location presents a unique set of technical and economic conditions that significantly affect results. This paper reviews current experience with such systems, and recent analysis and data that examines and quantifies potential benefits. The paper also highlights the factors that should be considered to perform a comprehensive assessment of the benefits from such systems.

An example of where the value of wind-hydro is recognized is in the Northwestern section of the United States. Despite some of the lowest power prices in the country, wind plant capacity installed in the states of Washington and Oregon has grown from less than 25 MW at the end of year 2000 to around 450 MW at the end of 2002. Decreasing wind energy prices, water shortages and growing demand for power in the region, and especially neighboring California, were factors driving this growth, along with increasing recognition that wind and water power, two variable resources can complement each other.

Hydropower and wind resources are also plentiful in the nine states in Northeastern United States, but wind has been slow to develop there. With less than 100 MW of wind installed in New England plus New York and Pennsylvania at the end of 2002, there is tremendous potential for wind to help meet increasing demand for power in the New England Power Pool (NEPOOL) and to improve air quality in the region. In addition, there is storage potential in the 35,000 MW of hydropower reservoirs in the neighboring Canadian Québec/Labrador power system. These dams account for about 61% of Canada's hydropower generating capacity. See Figure 1.

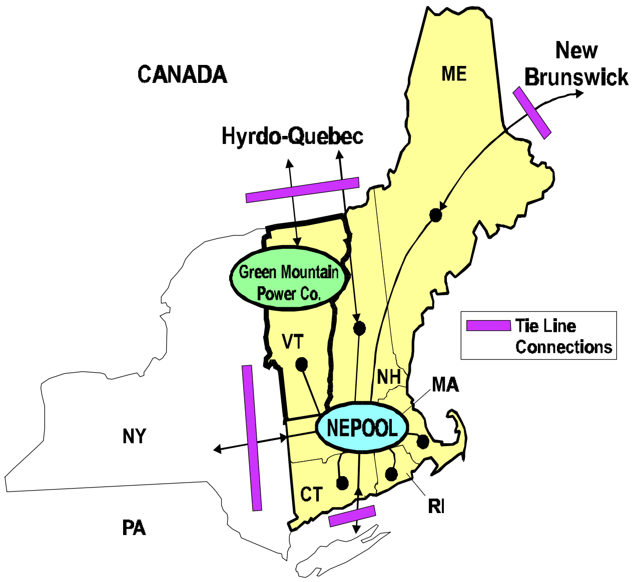

Figure 1. Interconnection of Vermont in the New England power pool (NEPOOL)

This unique combination of resources and growing demand for power led to a study that focused on the State of Vermont in U.S. where there is interest in developing wind and other renewable resources and where there are existing cooperative agreements and power exchange contracts between the cross-border power companies. The study methodology and results are the main topic for this paper.

A similar situation exists in Russia where efforts to develop wind resources have also been slow. Despite vast wind and hydropower resources, Russia has very low power prices due to the abundant low cost natural gas, coal, nuclear and hydropower. As a result less than 25 MW of wind plants are installed in the whole country to date. However, there is increasing interest in wind power especially in Northwest Russia where demand for electricity is growing 4-5% annually and power prices are increasing 8-15% per year. Recently, planning has begun for a 75 MW wind plant in the Leningrad Oblast near St. Petersburg where there has been a lot of industrial expansion.

From analyzing specific cases in the wind-hydro markets in the U.S., Canada and Russia, it is clear that each application can have significantly different goals, system power contribution, incentives, constraints and limitations. In all cases, wind can provide capacity firming for the hydro plants during low flow periods and vice versa. In addition, the combined plant's operation can increase flexibility to take into account other uses involved in water management including:

- Flood control
- Navigation
- Irrigation and agriculture
- Fish migration (Fish ladders)
- Recreation

Vermont Study

The State of Vermont and one of the major utility companies in the state, Green Mountain Power Corporation, are interested in developing wind and other renewable energy resources in the state. In a 1993 study by U.S. Department of Energy (DOE) laboratories to assess the resource potential of wind energy, Vermont was found to have good to excellent wind resources in many areas. Windy land areas, with class 3 (6.4 to 7.0 m/s average measured at 50 m above ground) and greater wind potential were found on 511 square kilometers (excluding land that is either in urban areas or environmentally protected, as well as half of forested area, 30% of farm land and 10% of open grazing land). This study suggested that up to 700 MW could be installed on this land, which accounts for only 2.1% of the land area in the State. That amount of wind capacity could produce an estimated 1-2 billion kWh of electricity annually. But at the time, such a large-scale wind energy development was considered to be impractical for the near term (<10 years) for several reasons. First, some of the sites were far from transmission lines and would be impractical to connect. Also at that time, there was no evaluation of the ability of the power system to accommodate this large amount of wind energy.

In 2001, DOE supported a second, cost shared study to assess "Wind and Biomass Integration Scenarios in Vermont." Princeton Energy Resources International (PERI), working with Green Mountain Power Corporation, the State of Vermont Department of Public Service, and Hydro-Québec, conducted the study. This effort evaluated the effects of high penetration levels of wind and biomass energy on the grid of Vermont (and adjoining areas) to determine: (1) transmission and distribution grid systems changes needed, (2) grid operation and control issues, (3) ways to minimize increases in the cost of energy to the consumer, (4) potential environmental benefits, and (5) the incremental cost of renewable energy capacity additions. This study also drew information from a detailed power systems study, conducted by General Electric 20 years earlier, on connecting 750 MW of turbines to the Vermont grid [Reference 1].

Since the current study approach is to examine impacts and conditions associated with introduction of a large amount of wind power, the first step was to update the assessment of available wind resource to determine if the state is resource constrained, regardless of the economics of wind power. Terrain maps were combined with wind data from the National Renewable Energy laboratory (NREL) in a digital Geographic Information System (GIS) format, and wind plant layouts were then developed on the GIS system using the same types of land use exclusions used in the 1993 and 1999 NREL studies [2]. Specifically, land was excluded for (1) environmental and siting concerns in areas like parks, hiking trails, scenic vistas, and endangered species zones; (2) excessive distances to the transmission or distribution system (5km or 1 km, respectively); and difficult terrain features. A detailed description of the analysis is available in a report on PERI's web site http://www.perihq.com/whats-new.html. Wind turbines used in the modeling were each assumed to be rated at 600 kW. Results from this site screening analysis showed that approximately 6,000 MW of potential wind capacity is available, compared to the current 1,000 MW of total generating capacity in the state. The study assumed that all required land would be available for wind plants. This is an important difference from the earlier studies where land use was more restrictive. Results were interpreted as an upper bound for potential capacity because there was no further screening based on site design feasibility, economic viability of the wind resource, or from the public acceptance perspective. The resulting detailed siting maps are available on the PERI web site. Out of the potential 6,000 MW wind resource, the study assumed that 810 MW would be installed, since this amount was close to the state's current peak load.

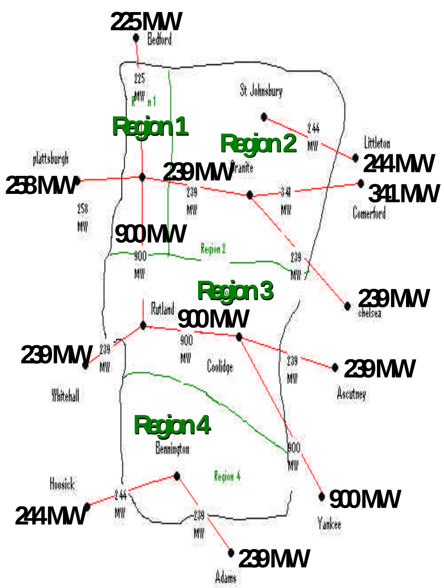

Figure 2. Vermont regional intertie links

Operational Modeling Assumptions

The target year for the modeling was chosen as 2010 so the load had to be extrapolated and adjusted and the following assumptions were made. Based on the trend over the last decade, it is assumed that, apart from wind and biomass, no other new generating capacity will be installed in Vermont over the next decade. The current power system in Vermont includes 992 MW of generation, composed of about 506 MW nuclear, 302 MW low-head hydro, 117 MW oil/gas fired, and 78 MW other including biomass and 6 MW of wind (data from 1999).

The year 2000 load curve was forecasted to year 2010 according to demand growth projections for each of four regions in the state shown in Figure 2. The expected annual growth rate for the state is 3.3% that resulted in an estimated 1.4 GW peak load in 2010.

Wholesale electricity prices were set to be the same on all links represented in the model and remain constant in real terms. Such an assumption means that Vermont demand for NEPOOL electricity would not influence the purchase/sale price in the New England area. The hourly price variations are based on the year 2000 scenario.

Next, operational constraints were applied to the wind and hydro plants. For the Vermont study, energy from the hypothetical wind plants was considered on a "must take" basis, provided the power system could handle the energy electrically and remain operationally stable. It was assumed that all wind energy could be used somewhere in the NEPOOL. Two cases were considered to evaluate the economic effect of adding the wind plant. In one Case the wind energy had to be sold to NEPOOL at the spot price for electricity. In the second Case wind energy could be exported and used in Canada. This is discussed in detail later in this paper and in [3].

Electrical System Model

Transmission Constraints

One of the important findings of this research is that there are no major system integration constraints to preclude wind power from becoming a large share of Vermont's power generation system. The study assumed that previously planned transmission upgrades would be implemented and that neighboring markets would accept the energy surplus from wind plants and will provide needed power when there is a lack of wind energy. The results from the simulations showed that no congestion is expected to occur on main internal and external ties of Vermont when 810 MW of wind capacity is installed within the state. Integrating so much capacity in the grid, at first may seem unrealistic, but this finding needs to be considered in the context that the Vermont power system is small compared to neighboring power systems. As such, Vermont relies on a set of important ties to NEPOOL in the eastern and southern regions, as shown in Figure 2, to allow the load to be continuously adjusted over time. The four regions shown in the figure were developed for this study to facilitate the modeling process. They are based on load growth patterns, wind resource availability, and presence of transmission capacity.

Intertie connections between NEPOOL and Canada occur at several locations (see Figure 1). For purposes of this study only existing intertie connections were considered through Vermont to the hydro-based power system operated by Hydro-Québec. The Québec/Labrador system is the largest power generating system in Canada. If private utilities are included, the regional system has 40,000 MW generating capacity with 95% hydro. Electricity is supplied mainly for the Québec load that is winter peaking (about 35,000 MW in 2002). However, for the past 20 years between 5 and 10% of that power has been exported to the U.S. annually. The 225 MW intertie line between Vermont and Hydro-Québec, along with the 75 MW tie line nearby in New Hampshire, are used to transfer the electric power.

Correlations

Correlations between Vermont load and wind, and NEPOOL load and price, were based on 2000 data. The correlation between Vermont wind and load was found to be weak in the short term (hourly), especially for peak load hours. However, we found strong correlation between wind and load on a seasonal basis. Likewise, the correlation between Vermont wind and NEPOOL price was found to be low. It should be noted that the regulatory process is changing and there is no clear pattern for spot market prices in the region. It is also possible that these findings represent a worst case, since they are based on wind characteristics from only one site (Searsburg wind plant in Southern Vermont) and one year of NEPOOL data.

The load on the Hydro-Québec system was found to correlate well with the wind resources in that region and with the wind in Vermont. Figure 3 shows this long-term correlation.

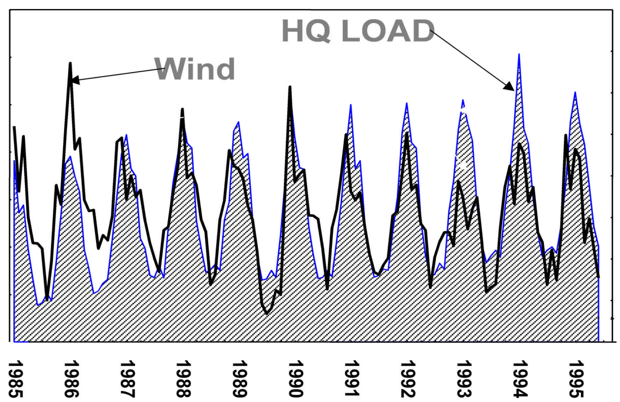

Figure 3. Hydro-Québec load correlated with typical wind in Vermont

Econometric Model

This phase of the study assessed the impact of integrating a high level of wind generating capacity on the cost of the Vermont electrical system in year 2010. The study considered the addition of a large amount of wind capacity to the grid to determine technical limits without major changes or reinforcement of the grid over a period of several years. Our methodology used, as a main building block, an existing hydrothermal medium-term generation planning (MTGP) model available at the Hydro-Québec Research Institute (IREQ). This model was previously modified at the Institut National de la Rechereche Scientifique (INRS) for assessing wind penetration on Hydro-Québec's power system. The general purpose of such a model is to optimize power system operation for a period that includes hourly load profile cycles analyzed for a full year duration. The objective of the model is to minimize costs while taking into account the full set of actual system operational characteristics (e.g., generation levels, load patterns, and wholesale power prices).

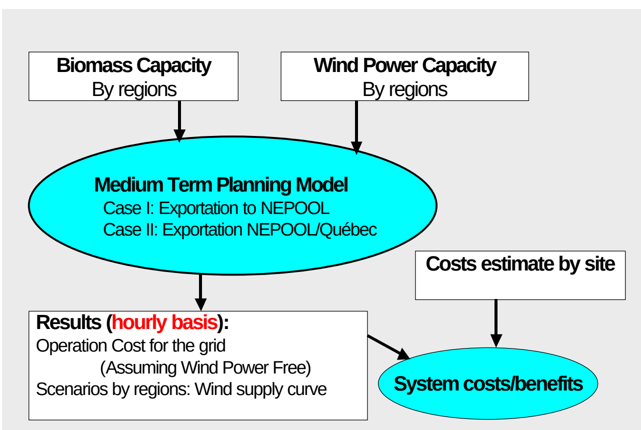

Figure 4. Schematic of economic modeling

The MTGP model was used as shown in Figure 4 to optimize operation of the Vermont generation system assuming 810 MW of wind power is located on the system, taking into account the interconnections with adjoining grids and actual hourly wind data from the Searsburg wind plant. The choice of this particular wind capacity number comes from the site characterization data developed in Phase 1 of the project to arrive at a capacity close to the state load and current generation capacity. It was assumed, for modeling purposes, that the Vermont generation system is operated in an optimal coordinated manner rather than in a decentralized competitive manner. The goal of the analysis was to identify the least cost way to complement the wind generation. This "complementary" generation could be provided either through interconnections to neighboring grids or by existing and/or additional backup power generation units connected to the Vermont grid system. In all instances, the transmission line capacity and electricity generation costs are accounted for in comparing scenarios.

Two general cases were investigated for operation of the Vermont grid. For Case I, Vermont was modeled to include energy exchanges with NEPOOL, and with Hydro-Québec only under current contractual conditions. That is, wind power is not allowed to be exported to Hydro-Québec in the model. For Case II, the model was extended to include export of wind power to Hydro-Québec, to measure the impact of this integration on the value of Vermont wind energy and on the optimization of critical water use in the hydro reservoirs, when wind is managed with virtually unlimited hydro storage capacities. [2] [4]

Correlations

For this study, NEPOOL hourly spot prices and load, and Vermont load and hourly wind resource characteristics (extrapolated from the Searsburg wind plant site) were the key factors driving the value of wind generation. The value of wind power in the NEPOOL market was heavily influenced by how well Vermont wind correlates with NEPOOL prices over the year. In addition, the level of correlation between the wind and load in Vermont is key to the level of benefits wind can provide to constrained parts of the distribution system (i.e., delay, reduction, or avoidance of distribution system equipment upgrades or reinforcements). However, even without such correlation, distributed wind installations can provide benefits such as voltage support and reduction of line losses. Finally, if wind energy is exported to Hydro-Québec, then HQ's load and price must be added to the list of critical factors. The relationship and correlation between all of the factors mentioned above is a fundamental underpinning of the modeling for this study.

Wind Energy Supply Curve

Since the primary goal of this phase of the project was to estimate the costs of integrating wind generation in Vermont, an important element of the analysis is the estimation of the levelized cost of energy (COE) for each additional increment of wind power that could be added to the grid. A set of such costs versus capacity is known as a "supply

Table 1. Financial Assumptions for Vermont Study

Parameter	Units	Assumptions	Comments
Business scenarios		IPP or GenCo with tax credits or municipal owner	
Wind plant cost	$/kW	1200 - 1425 (in year 2002 dollars)	Includes balance of station cost, range depends on size from 2MW to 60 MW+
Interest rates	%	7.5% for debt. After-tax return on equity is 13% for GenCo projects and 17% for IPP projects.	Minimum debt/service ratio assumed for IPP projects is 1.4.
Debt/equity ratio		100% debt for municipal owner; 35/65 for GenCo 50/50 for IPP	IPP would be 70/30 if they don't take the federal Production Tax Credit. Interest on debt is tax free for municipal owners
Debt term	Years	28 years	28 years is an optimistic assumption, based on 30 year project life. More typical of current market is 18 years based on a 20 year project.
Connection cost	$/km	100,000	Rough estimate based on knowledge of Vermont costs.
Production Tax Credit	$/kWh	$0.018/kWh for 10 years	Credit currently expires at end of 2003 but extension is expected. Credit not applicable to municipal owners.

curve." The COE was calculated using results from the wind resource extrapolation, terrain and plant layouts, combining with assumptions for current "favorable" financial and technology characteristics. "Favorable" characteristics include various potential combinations of financial factors and approaches, including (1) current low financing rates, (2) ownership by either independent power producer (IPP), investor owned generating company (GenCo) or municipally owned utility; (3) balance sheet financing or portfolio financing for GenCo's, where collateral for the project is set against the entire balance sheet of the equity owner, or against a portfolio of projects, thereby lowering the risk of default, and consequently the cost of capital; and (4) use of the Federal Production Tax Credit (PTC) or public utility ownership, which can utilize tax-free debt for project financing. The financial assumptions and ranges used in sensitivity studies are listed in Table 1.

Based on these assumptions, Figure 5 shows the estimated wind energy supply curve for the entire state in 2010. For the nineteen lowest cost projects totaling 810 MW on the statewide wind energy supply curve, COE estimates were 4.9-5.6 cents/kWh. The average COE from these nineteen projects, 5.4 cents/kWh, was used for modeling purposes. It must be emphasized that these cost estimates were made for parametric analysis, *not as a definitive estimate of actual project costs*. These COE estimates are in one sense an optimistic boundary in that the first nineteen (lowest cost) points from the supply curve were used and the financing assumptions for the COE calculation were "favorable," as described above.

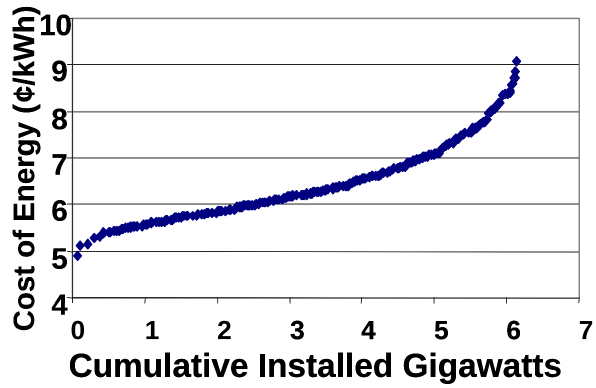

Figure 5. Wind energy supply curve for Vermont.

Cost estimates for the 19 projects did not include any individual siting feasibility analysis. However, there are several reasons why results may indeed be conservative. First, no attempt was made to reflect potential future wind turbine cost reductions resulting from technology advances from R&D, which given the relatively young stage of the technology, historical patterns, and projected R&D funding levels, are likely to occur. Second, no cost reductions were assumed to occur from economies of scale, learning, or other benefits related to increased cumulative or annual manufacturing and installation volume that will occur, by definition, in Vermont, as well as surely in the U.S. and other countries. Third, if 810 MW were installed in Vermont by 2010, it is probable that development of such a large amount of capacity would imply elimination/reduction of socioeconomic barriers that currently add cost to projects by creating delays or uncertainty (e.g. siting, zoning, interconnection, etc.) and would have been addressed by policy actions. Given these characteristics, the supply curve was judged to form a reasonable baseline from which to perform parametric analysis.

Russian Application

There are many similarities and some important differences between the US/Canadian situation and the wind-hydro opportunities in Northwest Russia. This is based on wind and hydro resource data that was collected in the Leningrad Oblast and the area surrounding Saint Petersburg as part of a feasibility study for a 75 MW commercial wind power plant project.

Hydropower is about 6% of the generating capacity in the Lenenergo system. There are six major reservoirs that total 655 MW. Plants identified as GES-10 and GES-11 are on the Vuoksa River north of Vyborg. GES-13 is on the river Narva near Estonia and GES-9 is on the river Svir. These plants were built primarily for power generation and also to help with flood control. Hydropower production is important in the overall power system because the largest source of electricity, large combined heat and power thermal plants, are most heavily loaded during the winter months.

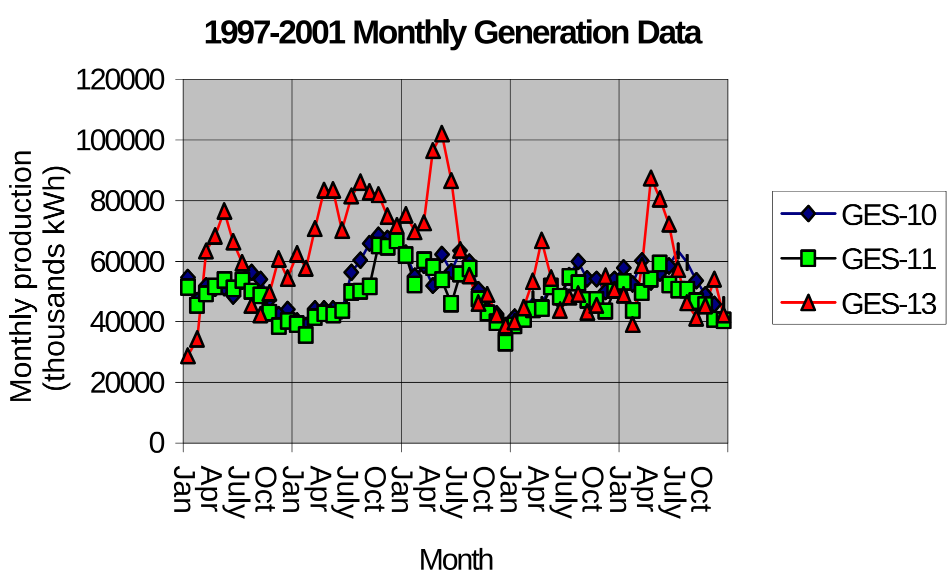

Figure 6. Russian hydroplants monthly energy production (1997-2001)

Electricity from hydroplants could be supported with wind power plants. The extremely cold winter climate in the Leningrad Oblast and sequestration of water in ice and snow causes major changes in the monthly energy production by key hydroplants. Five years of monthly energy production from three hydro plants showed seasonal variation in energy production could change by a factor of two or more from summer to winter. See GES-13 on Figure 6. During peak demand periods in winter months some of these plants are operated as peaking units and are shut down during off-peak demand periods to save water. See Figure 7. Annual peak daily demand in this region typically occurs in late December or early January. Wind plants could often provide support during these periods since windiest months occur between December and April when water flow is lowest and demand for heat and power are highest. This will further enhance the value of wind energy in the region.

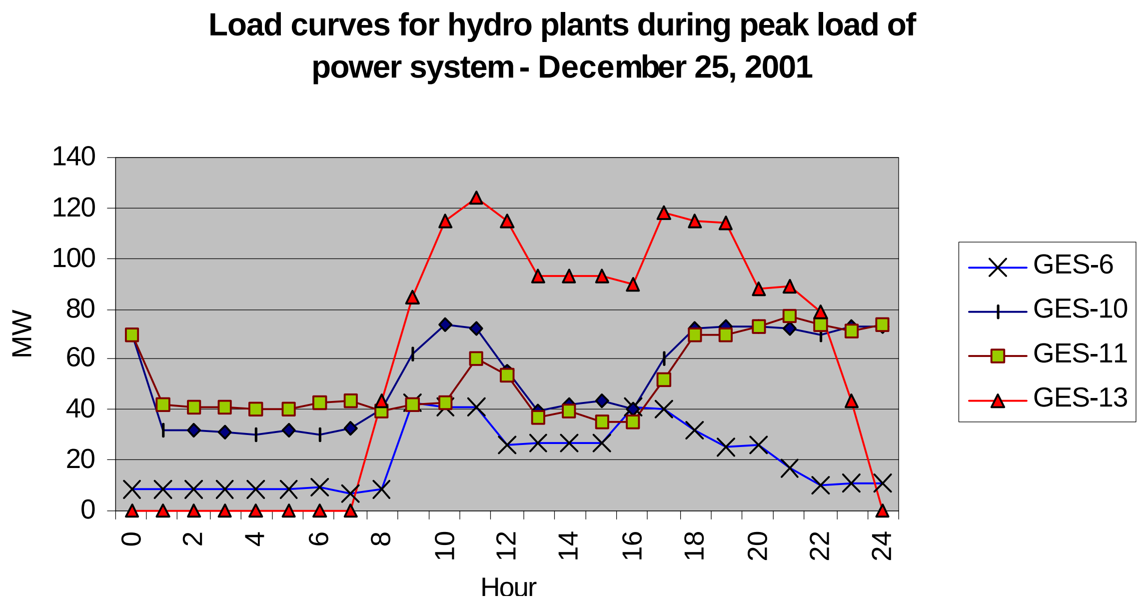

Figure 7. Russian hydroplants daily load curves during system peak demand period.

Conclusions

1. In the State of Vermont, 810 MW of wind plants could be added, doubling the state's generating capacity without significant upgrades or reinforcement of the transmission and distribution system.
2. Large amounts of wind energy could be added to the Vermont power system without creating congestion on existing in-state and external tie lines, providing neighboring regions would cooperate.
3. The value of wind energy is increased up to 22 % if large hydropower storage is available for release during peak demand periods and when wind and load are correlated.
4. Wind power plants can provide energy during critical winter months when hydro production is limited by low water flow and when electricity demand peaks in regions with extremely cold winters.
5. There are aspects of the wind-hydro system applications that have never been quantified including: environmental benefits and constraints (fish ladders, etc.), navigation and recreational uses. In some locations these are minor issues, but in others, they may have a significant impact on the overall system value.

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Key Words:

Wind, Wind-hydro, Vermont, Russia, Value, Grid, Integration