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Integration of Wind and Hydropower Systems: Results of IEA Wind Task 24

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ABSTRACT

In May of 2004, the IEA Wind Implementing Agreement (IA) established R&D Task 24, “Integration of Wind and Hydropower Systems.” Australia, Canada, Finland, Norway, Sweden, Switzerland, and the United States joined Task 24 with the goal of collaborating in the study of wind integration in a variety of electrical system configurations (load, generation, and transmission); hydro system configurations and characteristics; and market and operational configurations. Representing these countries were utilities and research organizations with the intent to understand the potential for and limiting factors in integrating wind into systems with hydropower. Case studies that analyze the feasibility, benefits, detriments, and costs of specific wind-hydro integration projects were the mechanism through which the goals of the task were addressed. The purpose of this article is to summarize the framework within which these studies were performed, and to present the key results and the general conclusions of the Task.

1. INTRODUCTION

Over the past several years, an emphasis on building new, clean, renewable energy resources has arisen, often manifested via politically mandated standards, a perceived need to cut carbon emissions, or the introduction of new, more cost-effective energy generation. Hydropower and wind power are examples of two renewable resources being called upon to meet the need for new generation, and they are also among the most affordable. Worldwide, hydropower generating capacity was responsible for 12.3% of electrical energy generation in 2007 (IEA 2008). International Energy Agency (IEA) statistics indicate that at the end of 2000, there was in excess of 410,000 megawatts (MW) of installed hydropower capacity within IEA member countries[1], with about half in Europe and half in North America. Since then, hydropower generation has increased by more than 13,000 MW in IEA member countries (IEA 2008). Hydropower is typically one of the least expensive generation sources, often outfitted with automatic generation controls (AGC) that allow very rapid response to changes in electricity demand able to supply valuable “ancillary services” required to

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[1] There are twenty-eight member countries, see http://www.iea.org/about/membercountries.asp.

maintain the instantaneous balance between generation and load. With its low-cost energy, and in some cases energy storage, hydropower is one of the most flexible and valuable generation assets on the grid.

Over the past decade, electrical energy derived from utility-scale wind turbines (greater than ~1 MW per turbine) has become cost competitive relative to bulk power prices and conventional electrical energy resources, especially natural gas based generation. Furthermore, as wind turbine technology has developed, turbine reliability has become very high and there is now significant experience in designing, financing, building, and operating large wind power plants. As a result, the installed capacity of wind power has increased dramatically during the last decade, from 15,400 MW in 2000 to in excess of 197,000 MW at the end of 2010 (IEA 2008, GWEC 2011). This significant growth is expected to continue over the next decade and beyond. In addition to its cost competitiveness, wind energy brings other benefits: it has long-term price stability, no emission of climate-change gases, requires no water, is an indigenous resource, and can foster rural economic development.

While wind energy has many positive aspects, it also has different generation characteristics than conventional utility resources. In particular, because meteorological processes drive wind, it is inherently *variable*. This variability occurs on all time frames of utility operation from real-time, minute-to-minute fluctuations through yearly variation affecting long-term planning. In addition to being variable, it is also a challenge to accurately predict wind energy production on the time scales of interest to utility planners and operators: day-ahead and long-term planning of system adequacy. Wind energy is more predictable in the hour-ahead time frame, but even then, the *uncertainty* in wind forecasts can be non-trivial and must be accounted for in utility operation and dispatching.

In order to minimize impacts and maximize benefits, each utility or balancing area[2] (BA) that incorporates wind energy must learn how to accommodate its *uncertainty* and *variability* in operational and planning practices, and to do so while maintaining system reliability. A system that includes hydropower in its pool of generating resources may be well suited to accommodate wind energy due to hydropower's inherent flexibility. That said, hydropower also possesses different operating characteristics that warrant special consideration, as compared to flexible thermal generation resources (e.g., simple cycle gas turbines). For example, run-of-the-river hydropower must be used or spilled[3] at times when the water is naturally flowing, limiting its flexibility. Alternatively, hydropower facilities with large reservoirs may have considerable discretion in regard to when water is released, providing significant flexibility. On river systems with multiple hydropower facilities, water releases at an upstream dam will likely influence and constrain the water releases and power generation at the downstream dams. This interaction on a river system—especially for one in which multiple owners or operators are involved—may require joint planning and the development of complex operating practices that will permit some form of optimal, coordinated operation between the facilities, or at least fair operation.

Given this background and due to the potential for synergistic operation of wind and hydropower facilities within or across balancing areas, and considering the unique

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[2] A balancing area is taken here to be a subset of the broader interconnected transmission system for which a single transmission system operator or balancing area authority is responsible for maintaining grid safety and reliability standards.

[3] *Spill* refers to water that is passed through a hydropower facility but not used for power generation. Frequently this water passes over or through the *spillway* on a dam.

Table 1: Task 24 member countries, contracting parties, and participants

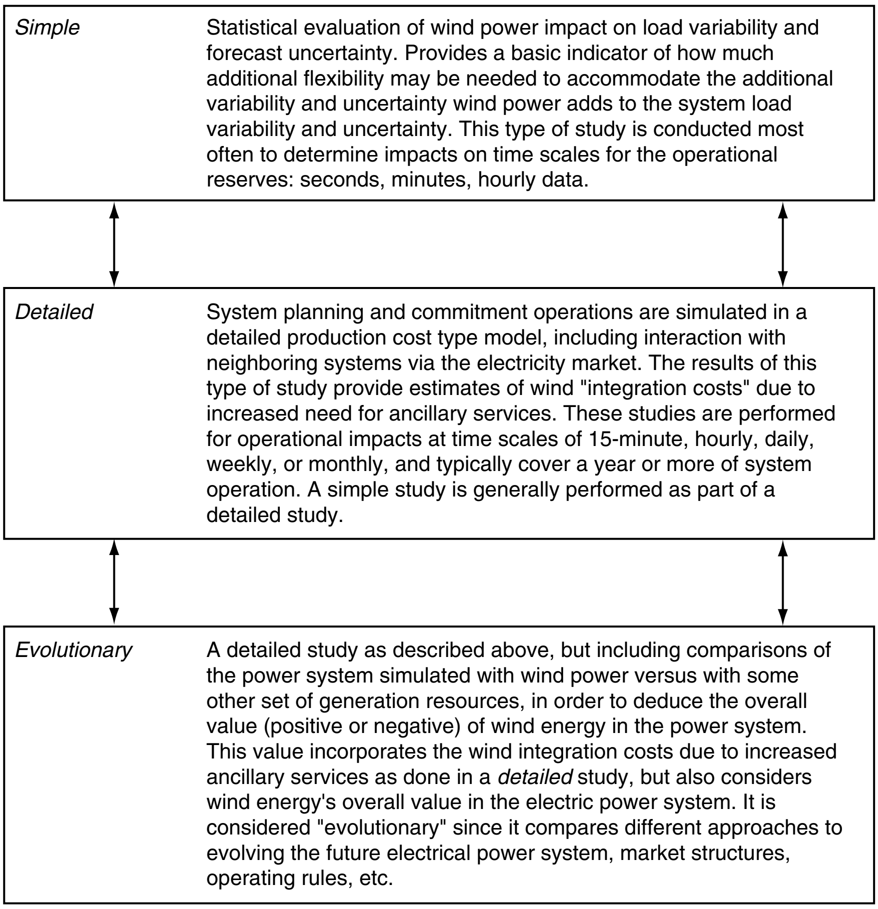
Country	Contracting party	Participant
Australia	Australia Wind Energy Assoc.	Hydro Tasmania
Canada	Natural Resources Canada	Natural Resources Canada Manitoba Hydro Hydro Québec
Finland	TEKES National Technology Agency in Finland	VTT
Norway	Norwegian Water Resources and Energy Directorate	Sintef Energy Research Statkraft Energy
Sweden	Swedish Energy Agency	KTH Swedish Institute of Technology
Switzerland	Swiss Federal Office of Energy	EW Ursern
United States	U.S. Department of Energy	National Renewable Energy Laboratory Grant County Public Utility District Sacramento Municipal Utility District Northern Arizona University

operating constraints and complexities prevalent with hydropower, utilities and researchers from several countries expressed interest in investigating "wind and hydropower integration" through broad collaboration and information sharing. In November 2003, the IEA Wind Implementing Agreement (IA) convened Topical Expert Meeting #41 on the "Integration of Wind and Hydropower Systems" in Portland, Oregon, USA. As a result of this meeting, a proposal was introduced for the IEA Wind IA to form an "Annex" or "Task" to foster international collaboration in studying the potential for integrating wind power in electrical systems with hydropower. In May of 2004, the Wind IA established Research and Development (R&D) Task 24, "Integration of Wind and Hydropower Systems." The member countries, contracting parties, and participating organizations in the Task are listed in Table 1. The goal of the collaboration established was to study wind integration in a variety of electrical system configurations (load, generation, and transmission); hydro system configurations and characteristics; and market and operational configurations—all of which is more than could be studied by any one country alone—and to understand the potential for and limiting factors in integrating wind into systems with hydropower.

Case studies that analyze the feasibility, benefits, detriments, and costs of specific wind-hydro integration projects were the mechanism through which the goals of the task were addressed and the feasibility of wind-hydro integration was investigated. The outcome of the task was a two volume final report (Acker 2011a, Acker 2011b), which serves as the primary source for the material presented herein. With their focus on wind integration in systems with hydropower, these reports complement other reports related to integration of variable renewable resources (Holttinen et al. 2009, IEA 2005, IEA 2008a, Acker et al 2010, Acker 2011c, Acker and Pete 2011d, Matevosyan 2006, GE Energy 2010, Hirst 2002, Smith et al 2007, Westrick et al 2003). The purpose of this article is to summarize the framework within which these studies were performed, and to present some results and the general conclusions of the Task. For clarity, the results are divided into three sections depending on the main focus of the case studies: grid integration case studies, hydropower impact case studies, or economics case studies. Each participant in Task 24 contributed one to three case studies, each of which are described briefly in the relevant results sections.

2. FRAMEWORK OF WIND-HYDRO INTEGRATION STUDIES

Wind power is typically absorbed into the power system when it is generated, just as the load is served at the time it is required; therefore, it is convenient to look at the system's load less wind (i.e., the system load with the wind power subtracted) also referred to as *net load*. The remaining power system must balance net load via unit commitment, load following, and regulation. In essence, wind power is treated similar to negative load, and the foundational data of virtually all wind integration studies is analysis of the net load. Power system studies for wind integration may differ in many ways, some trivial and some significant, beginning with the complexity and detail of the study method and the assumptions employed. In regard to overall scope, wind integration studies can vary from simple to detailed to evolutionary, as illustrated in Figure 1. A *simple* study typically looks only at the effect of wind power on system net load, and in particular the variability of that net load; a *detailed* study involves simulation of the system operation in order to deduce the impacts and costs of wind integration; and an *evolutionary* study simulates the system like a detailed study does, but goes further to consider the overall value of the wind energy, and possibly considers changes in how the system is constituted, constrained, and operated, in search of better ways to incorporate wind into the power system or to operate hydro in the system. The case studies conducted for Task 24 were primarily *detailed* in type, but some were *simple*. It is worth noting that studies are also conducted to determine dynamical effects on the electrical grid, for network stability, etc.; these types of studies were not



Simple	Statistical evaluation of wind power impact on load variability and forecast uncertainty. Provides a basic indicator of how much additional flexibility may be needed to accommodate the additional variability and uncertainty wind power adds to the system load variability and uncertainty. This type of study is conducted most often to determine impacts on time scales for the operational reserves: seconds, minutes, hourly data.
Detailed	System planning and commitment operations are simulated in a detailed production cost type model, including interaction with neighboring systems via the electricity market. The results of this type of study provide estimates of wind "integration costs" due to increased need for ancillary services. These studies are performed for operational impacts at time scales of 15-minute, hourly, daily, weekly, or monthly, and typically cover a year or more of system operation. A simple study is generally performed as part of a detailed study.
Evolutionary	A detailed study as described above, but including comparisons of the power system simulated with wind power versus with some other set of generation resources, in order to deduce the overall value (positive or negative) of wind energy in the power system. This value incorporates the wind integration costs due to increased ancillary services as done in a *detailed* study, but also considers wind energy's overall value in the electric power system. It is considered "evolutionary" since it compares different approaches to evolving the future electrical power system, market structures, operating rules, etc.

Figure 1: Illustration of the range of complexity that can be employed in "wind integration" studies (Acker 2011b).

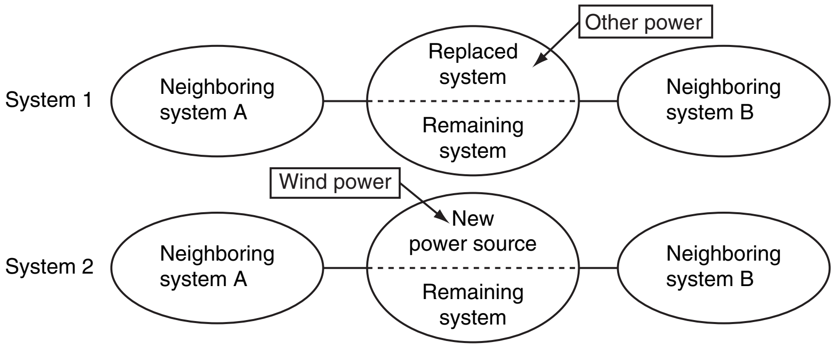


Figure 2: Deducing integration costs by comparing the costs of operating two variations of the electrical system, one with wind and one with some other set of generation resources. Source: Söder and Holttinen (2008).

included as part of Task 24 and were addressed in IEA Wind Task 21 – Dynamic models of wind farms for power system studies.

Söder and Holttinen (2008), pursuant to discussions held as part of the Task 24 dialogue, published an article describing different ways of setting up and performing a wind integration study in order to provide a consistent framework to formulate an integration study as well as interpret and compare results from the various studies. Adapted from their paper, Figure 2 provides an illustration of two systems (that is, balancing areas) that are otherwise identical except that System 2 possesses some amount of wind power while System 1 includes some set of "other power" generation resources that would be "replaced" by the wind power. The other power sources in the replaced system could be thermal generators, nuclear systems, etc., existing on the system or they could be new, but in either case would be some realistic set of resources that could be employed.

The "remaining system" shown in both Systems 1 and 2 represents the remaining power system and is identical in both systems, as are neighboring systems A and B and the interties with them. Depending on how the replaced system is defined, and the assumptions employed in modeling both Systems 1 and 2, the study could be classified as either detailed or as evolutionary, as presented in Figure 1. The essential difference between these classifications, as defined here, is that a detailed study will mimic system operation in a way to deduce the operating cost increment associated with wind energy's variability and uncertainty, whereas an evolutionary study will consider the "integration cost" as the difference in operating costs (O) for the two systems, assuming each is run optimally given its technical and economical specifications, including any investments (I) that might be made that reduce the overall operating cost. Thus,

$$Integration\ cost = (O_{wind} - O_{replaced}) - (I_{wind} - I_{replaced})$$

This simple equation applies for any type of integration cost study. However, for an evolutionary study, modeling of the system need not be conducted given the existing transmission constraints, market rules, scheduling intervals, etc., of the electrical system as presently configured, but rather can consider changes intended to *evolve* the system to a more efficient, profitable, and/or lower cost realm of operation.

Before proceeding to the case study descriptions and results, it is useful to discuss what is meant by "the penetration level of wind energy." When wind integration costs or impacts are presented, "wind penetration" is almost universally cited to provide an indication of how much wind power is being assimilated into the balancing area for which the integration impacts and costs are incurred. There is usually some implication that systems of a similar wind penetration should experience similar wind integration impacts, but this is not necessarily the case. Perhaps the two most frequently cited definitions of wind penetration are given by the following simple expressions, based upon either peak system load or annual energy consumption:

Wind power peak penetration = (installed wind power capacity)/(system peak load)
OR
Wind power energy penetration = (annual wind energy output)/(annual system energy consumption)

While other metrics for the wind penetration exist (e.g., (installed wind power)/(minimum load)) and are useful, the two given above are the most common and were used in the case studies contributed to Task 24. Unless otherwise specified, the wind penetration levels stated in the following were computed based upon the annual system energy consumption.

3. GRID INTEGRATION CASE STUDIES AND RESULTS

System balancing is one of the primary functions performed by a transmission system operator (TSO). Ancillary services is the term frequently used to describe the services or functions related to the operation of a balancing area within an interconnected electric power system necessary for maintaining performance and reliability. These services can be broadly categorized as operational reserves or contingency reserves, and include unit commitment, load following and regulation. Operational reserves are generally used to respond to fast fluctuations in total system net load as well as the more gradual and more predictable ramps in net load. Contingency reserves are generation resources, some fast responding and synchronized and some off-line that can be brought on-line and synchronized relatively quickly (within 10- to 30-minutes, depending on the system), utilized to cover unexpected losses in generation or transmission resources. Grid integration studies are frequently aimed at determining the increase in operational and contingency reserves, and their related costs, caused by the variability of wind power and uncertainty in its prediction.

The wide variety of hydropower installations, reservoirs, operating constraints, and hydrologic conditions combined with the diverse characteristics of the numerous electrical grids provide many possible combinations of wind, hydropower, balancing areas, and markets, and thus many possible solutions to issues that arise. Six of the seven countries participating in the Task have contributed at least one case study of this nature, covering a wide variety of system configurations, with some representing small systems (<1,000 MW peak load), such as Grant County Public Utility in Washington State, USA, to large systems (>74,000 MW peak load) such as Nordic system. There is also a wide variety of hydropower facilities, with some being essentially run-of-the-river with little storage capacity (a day or two), to very large hydro plants with multi-year storage capability. Seven case studies of Task 24 addressed wind integration impacts and costs in systems with hydropower, the relevant conclusions of which are summarized below.

- *Finnish case study #1*: In this study Holttinen and Koreneff (2012) showed that even with the limited flexibility of hydropower (run-of-the-river with small reservoirs), a large part of wind power forecast errors can be provided for by shifting hydropower back and forth inside one day. The study also showed that when correcting the forecast errors of wind power at a large balancing market in which hydro power produces most of the balancing (like in Nordic countries), there is not a great benefit of combining/integrating wind power and hydropower at a single producer. It is more cost effective to bid all flexibility of hydropower to the balancing market and use it from there to correct the system imbalances than to use it for dedicated balancing of wind power.

- *Finnish case study #2*: The study analyzed wind power energy penetrations of 10%, 20%, and 30% in the Nordic system (74,000 MW peak load), with the intention of determining whether or not there is enough regulation available from the hydropower to deal with incremental increase in net power system variations and forecast errors due to wind power (Kiviluoma and Holttinen (2006) and Kiviluoma et al. (2006)). The study identified a practical system configuration of 60% of electricity from hydropower, most of which being reservoir hydropower, and 30% of electricity from wind power. Results showed that a large part of hydropower capacity should be capable of flexible operation and able to provide the additional regulation required due to the high penetration of wind power.
- *Norwegian case study #1*: This case study analyzed a regional power system with an assumed 420 MW power transfer capacity (Korpås et al. 2006). With regards to integrating wind energy, the most conservative approach allows for only 115 MW of wind power in the constrained network with 420 MW of capacity, as this will not require any control actions even in the very unlikely case of maximum wind and hydro generation (115 MW + 380 MW) at the same hour as the historically lowest consumption (75 MW). The results of the study showed that for the specific system under consideration, up to 600 MW of wind power is possible—without noticeable reduction in income from energy sales compared to an ideal non-congested case—by applying coordinated operation of the wind power and hydropower plants.
- *Norwegian case study #2*: This case study considered the impact of wind power on system adequacy, assessed using data from a real-life, regional, hydro-based power system (Tande et al 2006). Three cases were considered: the installed wind power is 62 MW (Case B) and 1,062 MW (Case A and Case C), which correspond to wind power penetration levels based upon peak system load of 1.6% (Case B) and 28.1% (Case A and Case C). The annual system energy consumption for the study year was 21,024 GWh, which gives wind energy penetration levels of 0.9% (Case B) and 15.2% (Case A and Case C). The study concluded that wind power will have a positive effect on system adequacy in a regional hydro-based power system. Wind power contributes to reducing the Loss of Load Probability (LOLP) and to improving the energy balance. Adding 3 TWh of wind or 3 TWh of gas generation are found to contribute equally to the energy balance, both on a weekly and annual basis. Both wind and gas improves the power balance. The capacity value of gas is found to be about 95% of rated, and the capacity value of wind about 30% at low-wind energy penetration and about 14% at higher wind penetration.
- *Swedish case study #2*: The aim of the simulation in the second Swedish case study was to study the possibility of balancing wind power in northern Sweden using hydro power in northern Sweden (Amelin et al 2009). The simulation included a total installed capacity of 795 MW of wind power, and that output was scaled to 1,000, 4,000, 8,000 and 12,000 MW. All hydro power stations larger than 10 MW in the study area were considered, i.e. 154 hydro power plants with a combined capacity of

13.2 GW, which corresponds to about 80% of the installed capacity of all hydro power in Sweden. The conclusion of the study was that the existing hydro power in northern Sweden has sufficient installed capacity and is fast enough to balance even large amounts of wind power. The model did predict spill to occur, but that to an overwhelming extent such spill that can be avoided by using efficiency tools for season planning. Only in a few cases–and then in particular for a wind power expansion of 12,000 MW–will there be spill that depends on insufficient balancing capability in the hydro power.

- *U.S. case study on the Missouri River*: This case study analyzed wind integration into the balancing area operated by the Western Area Power Administration (WAPA) and supplied by hydropower facilities located along the Missouri River (Acker 2011b). The study considered integrating five levels of wind power penetration of 3%, 3.7%, 9.3%, 18.6%, and 37%. The hydro power capacity is 2,400 MW from six hydro facilities containing multiple years of water storage, and the peak system load was 2,700 MW. The statistical study concluded that in the WAPA system, significant operational impacts from wind energy – those that must be dealt with in planning and operation (regulation, load following, system ramping of net load) – will likely arise when the wind penetration approaches 500 MW (about 18% of the peak system load).
- *U.S. case study Sacramento Municipal Utility District*: This case study focused on hydropower resources along the upper American River and operated by the Sacramento Municipal Utility District (Zavadil 2008). Hourly simulation cases were completed for at least one full year of data for four proposed wind generation penetration levels: 102 MW, 250 MW, 450 MW, and 850 MW. These correspond to the following wind penetration levels (computed by dividing wind capacity by system peak load): 2.7%, 6.7%, 12.1%, and 22.8%. The study found lower penetrations of wind generation have only a small impact on fast regulation requirements, but begin to dominate as the penetration increases. Wind integration costs were computed to range from about $2 to $8 per MWh of wind energy produced. The results show a very substantial reduction in operating cost and integration costs with the hypothetical Iowa Hill pumped-storage facility operating (with savings as much as $5/MWh). Furthermore, the results also show that integration costs decrease with increasing diversity of wind generation assets.
- *Canadian case studies of Hydro-Québec's system*: Three related case studies were performed by Hydro-Québec, each considering wind power energy penetration of 5% in the Québec power system (3000 MW wind), which has a peak load in the winter of approximately 37,000 MW supplied primarily by hydropower.
- *Hydro-Québec study #1*: The first study determined the impacts of wind power on operational reserves, specifically on AGC and load following reserve (de Montigny et al. 2010, Kamwa et al. 2009). Two approaches for computing regulation were compared (statistical analysis using analytical time series and IREQ simulation, and IREQ is the Institut de recherche d'Hydro-Québec), and also two methodologies for evaluating regulation impacts (Hirst and Kirby's ORNL method (1999) based on standard deviation and the BPA method (BPA 2009) based on variance allocation). Results demonstrated that the IREQ simulator appears to be the proper tool for obtaining the most accurate analysis of the impacts due to its far more realistic system operation assumptions. In this case, the supplementary AGC and load-following reserves amounted to 1% and 5%, respectively, of the wind power capacity.

- *Hydro-Québec study #2*: The second study utilized a methodology based upon a modified loss of load probability technique for the computation of balancing reserves, based on risk criterion on the horizon of 1 to 48 hours ahead (Menemenlis et al. (2009) and Menemenlis et al. (2010)). These reserves essentially address economic aspects of short-term supply adequacy, may vary a lot depending of the season and the meteorological conditions, and consist of available generating capacity that could be deployed when needed to offset discrepancies in supply caused by errors on current forecasts. Traditionally, these reserves have covered uncertainties on load forecasts and forced outages. The results showed that with current Hydro-Québec balancing reserves being relatively high and risk levels relatively low, little additional balancing reserves are required to integrate 3,000 MW of wind power capacity. Further, since the balancing reserves come at a cost, the risk level to maintain with additional reserves is an economic decision.
- *Hydro-Québec study #3*: Finally the last study considers the impacts on the system capacity adequacy taking into account the Nordic weather conditions on the wind turbines availability (Bernier and Sennoun (2010) and Choisnard et al. (2010)). The study model relied on wind and load data series that were matched on an hourly time-step, over a 36 year period using real weather data combined with seven different weekday pattern. The model takes into account forecasting errors and conventional generation outages through Monte-Carlo simulator, and the capacity contribution results from the comparison of two simulations leading to the same reliability target with the loss of load expectation equaling to one day per ten years. Results showed the capacity credit was established at 30% of total wind power capacity. Results were found to be very sensitive to wind data during a limited number of extreme cold events over the 36 years period of the study.

4. HYDROPOWER IMPACT CASE STUDIES AND RESULTS

Depending on the relative capacities of the wind and hydropower facilities as well as the remaining generation, wind integration may necessitate changes in the way hydropower facilities operate in order to provide balancing, reserves or energy storage. These changes may affect operation, maintenance, revenue, water storage, and the ability of the hydro facility to meet its primary purposes. Beyond these potential changes, integration with wind could potentially provide benefits to the hydro system related to water storage or compliance with environmental regulations (e.g., fish passage) and create new economic opportunities. Thus, the purpose of these case studies was to increase understanding of the impacts and benefits of wind integration on other aspects of the hydro power system.

Hydropower generators are inherently flexible, but in practice their flexibility depends on a host of factors. The type and magnitude of ancillary services and reserves that can be provided by a hydropower plant depends on whether it possesses significant storage or if it is a run-of-the-river plant with limited storage. The flexibility of operation also depends on whether or not the hydropower is part of a cascade of dams on a river system, and the level of coordination between those on the same river. Hydro facilities often have numerous functions—power generations being one—that guide their operation and define their flexibility. Layered on top of the physical and functional planning, there may be numerous organizations and stakeholders involved, along with differing market or economic situations. It is the interaction of the many functions, system configurations, and stakeholders that establish the authority, priority, and economics that govern the potential for wind and hydro integration.

The overarching question for studying wind and hydropower integration is whether system-operating impacts due to wind power can be accommodated by hydropower within the constraints currently in place on hydropower (or not easily changed), and in an economically advantageous way. And if so, what changes will this cause to hydropower operations or costs? In concept, hydropower should be able to provide short- to medium-term buffering of the enhanced variability and uncertainty wind power induces in the overall load net wind. Adding wind power to the system may or may not help hydropower meet power and other system demands, and the influence on other hydro functions, such as water deliveries, must be considered. That said, even within the constraints currently imposed on hydropower, it is a valuable system balancing resource, and possesses the inherent qualities needed to facilitate wind integration. Three of the seven countries participating in Task 24 contributed five case studies addressing hydropower impacts, the relevant conclusions of which are summarized below.

- *Australian case studies #1 and #3*: Hydro Tasmania's system was modeled with 1,850 MW of peak load, a 900 MW minimum load, 2,267 MW of hydropower and 630 MW/480 MW export/import capability via an HVDC interconnect with the Australian mainland. The studies found that a high level of wind power can be integrated into the Tasmanian system, up to 1,300 MW, if the interconnect with the Australian mainland is utilized and if measures are taken to address low system inertia, shortage of fast FCAS (Frequency Control Ancillary Service) and low fault levels. The study also identified that commitment of additional hydro generators operating in either synchronous condenser mode or tail water depression mode can largely improve the integration of the wind generation in Tasmania and problems associated with low system inertia.
- *Australian case study #2*: With respect to reservoir storage, in the case of islanded operation of a Tasmanian power system, system storage is unable to effectively absorb all output from large-scale wind generation due to coincident of high winds and high inflows. There is an increasing negative impact on storages as wind generation capacity is increased. Interconnecting to the Australian mainland, via the addition of the high capacity HVDC interconnection, significantly increase the ability to integrate wind generation in Tasmania without a negative effect on the energy in storage.
- *Swedish case study #1*: The first Swedish case study analyzed the possibility of balancing wind power with hydropower plants located along one certain river (for details, see Söder (1994) or Acker (2011b)). The amount of wind power studied extrapolated to a penetration in whole Sweden was equal to 6.5–7.5 TWh/year, or 5% of total energy production per year. The results from the simulations indicate that Swedish wind power installations that generate about 2–2.5 TWh/year do not affect the efficiency of the Swedish hydro system. At wind power levels of about 4–5 TWh/year, it is estimated that the amount of installed wind power should be increased by about 1% to compensate for the decreased efficiency in the hydro system. At wind power levels of about 6.5–7.5 TWh/year, the additional wind power needed to compensate for loss of hydro efficiency is about 1.2%, but this figure has to be verified with more extended simulations.
- *U.S. case study Grant County PUD*: This case study considered two hydropower plants located along the Columbia River and operated by the Grant County Public Utility District No. 2 (Grant PUD) (Acker et all 2007). The levels of wind penetration considered in were 12 MW (1.8%), 63.7 MW (7.8%) and 150 MW (18.6%), with each percentage computed as a percentage of peak load (including sales of energy).

Study results for the 2006 data year suggest that the overall impact on system statistics for regulation and load following is quite modest, even at a wind energy penetration of 150 MW. The small statistical impact suggests that, absent other constraints, the physical generation resources are sufficient to handle wind variability at this level. However, due to changes in the distribution of load following hourly changes, there are some potentially significant operational challenges in scheduling the resources without infringing upon system constraints. To address this, an hourly simulation was conducted using day ahead wind power forecasts, revealing that additional instances of dipping into contingency reserves occur due to missed wind power forecasts, and that additional short duration excursions below the minimum flow requirements (for fish survival) also occur. The increases, however, are only modest and many can likely be handled during the day of operation, though at some cost.

5. MARKET AND ECONOMIC CASE STUDIES AND RESULTS

The wind integration and hydro system impact studies have demonstrated the technical feasibility of integrating wind power and hydropower, even in systems with either transmission or hydropower constraints. Beyond the technical feasibility, two case studies investigated whether or not integrating wind was practical from an economic point of view, or looked at the effect of wind integration on the market. These two studies represent a valuable contribution to the Task, and are a good start in addressing the overall question of economic feasibility.

- *Canadian case study*: Natural Resources Canada conducted a study for a small public utility in the U.S. along the Columbia River, concluding that utilizing wind power to address load growth is economically feasible (RETSCREEN 2009). It was also shown that the hydropower resources available to the utility being study were satisfactory to supply low-cost balancing resources. Compared to actual data from the utility, due to underproduction of the wind power plant compared to that estimated for the study year, it was found that the wind power would not have been economically favorable without Renewable Energy Production Incentives.
- *Finnish case study #2*: The study analyzed wind power energy penetrations of 10%, 20%, and 30% in the Nordic system (74,000 MW peak load) (Kiviluoma and Holttinen (2006) and Kiviluoma et al. (2006)). Because old power plants were not retired in the study, there were no problems with system adequacy. Balancing this amount of wind power was shown to be feasible, but it was determined that a large penetration of wind power in a hydro-dominated power system will lower the spot price of electricity dramatically, which creates a challenge to get new investments in the system. It is unclear whether this kind of system could arise based on the markets even if it would be the most cost-effective way to serve load from a system perspective.

6. OBSERVATIONS AND CONCLUSIONS

As the breadth of the case studies indicate, integrating wind and hydropower can be quite complex. A summary of some key observations and conclusions from the work and discussion among the participants are provided below:

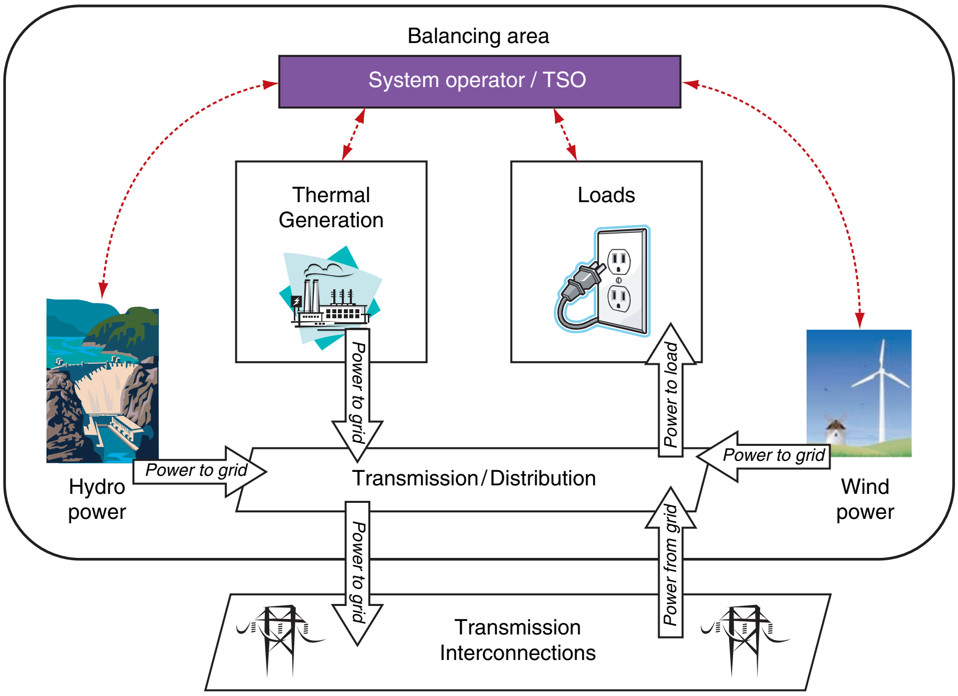


Figure 3: A practical configuration for wind and hydropower integration (Acker 2011a).

- Figure 3 provides a conceptual view of a practical configuration for combining wind and hydropower in a balancing area. The key take away from this illustration is that wind and hydropower are system resources that help serve the load via the transmission grid, and that they are each controlled by the transmission system operator. The incremental impacts of wind integration is typically best handled in the context of the entire system, with all of its load and generation resources, and not in isolation from them, (i.e. not one wind power plant balanced by one hydro plant to produce a flat output).
- When addressing wind integration, one should consider the holistic impact of wind power on the system (e.g. a cost-benefit analysis directed toward the electricity customer and effect on transmission system reliability), and not just the enhanced balancing requirements due to wind power's variability and uncertainty. E.g., wind power will enhance balancing requirements and incur an "integration" cost; however, at the same time the overall cost of electricity to the consumer may decrease due to wind energy displacing higher cost generation resources.
- The setup and operation of the transmission system and balancing area authority will have a profound impact on the ability to integrate wind power and the integration costs incurred. TSOs in which the timing of transactions (committing units, buying and selling of electricity, ancillary services, and reserves) is frequent are more capable of integrating wind power and at lower costs.
- Transmission interconnections are important factors in limiting or enhancing wind integration in system with hydropower due to transmission constraints or congestion (or lack thereof), or facilitate integration via power exchanges with neighboring systems. Larger balancing areas can more easily integrate wind and hydropower.

- Electrical systems may function within a liberalized electricity market, in a vertically integrated utility that participates with neighboring systems via bilateral transactions, or some combination of the two. Wind integration costs and impacts tend to be reduced in market systems, especially those with many market actors and flexible resources.
- The wind/hydro case study results were consistent with other wind integration studies in that the presence of an efficient and liquid electricity market has a large positive influence on the economics, frequently dominating all other factors. Furthermore, an important factor in interpreting the economic consequences of integrating wind and hydro is the perspective taken by the study: for the overall benefit of the electric customer vs. a single actor in the market (e.g. a utility, a wind developer, etc.).
- In conducting wind integration studies, the modeling assumptions and techniques can have a significant influence on the results. Thus, these should be well specified and understood when interpreting results and comparing different studies. Wind integration studies often involve the use of production cost models (PCM) that simulate hourly operation of the power system. General PCM models (those not specifically developed for or by a hydropower-dominant utility) need improvements in how they model hydropower operation, water balances, and constraints, in order to better investigate the nuances of wind and hydro integration (e.g. the impact of enhanced system balancing requirements on hydro system constraints, or the ability to model the constraints, etc.). Virtually all PCM models require further improvement in how they handle wind power and wind power forecasts.
- At low wind penetration levels (~1%), wind integration impacts and costs are minor. These transition to more cost and complexity as penetration levels increase to ~20%. Beyond ~20%, changes in system operational practices are likely necessary to optimally integrate wind and hydropower (e.g. use of advanced wind forecasting models incorporated into system planning, etc.). Islanded or small power systems with weak interconnections may more readily experience the effects of the enhanced variability in net load and increased reserve requirements caused by wind integration, including impacts on system inertia, and require attention in system planning.
- Non-power constraints on the hydropower system can influence the ability to integrate wind and hydropower. Such constraints may include higher priority functions of the hydro facility that dictate how water is run through the generators, such as irrigation water deliveries, environmental regulation (e.g. fish passage), recreation, or flood control. While these non-power constraints are important, they frequently occur on time scales of system operation different than those related to wind/hydro integration. Thus they do not tend to be prohibitive and often may not significantly influence the wind and hydro integration, although at times they do reduce hydro system flexibility. Of the Task 24 participants, these constraints only played a significant role in hydro systems in the United States.

In summary, while hydropower systems possess special characteristics and operating constraints, the inherent flexibility of their generators and the potential for energy storage in their reservoirs make them well suited to integrate wind into the power system. As wind penetration increases, the agile hydro generation can address wind integration impacts and this service represents an economic opportunity for many hydro generators.

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