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Simulation of a More Renewable Energy Mix for Ontraio

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Incorporating renewable energy into the grid in the form of wind power poses many challenges to grid operators due to its intermittent and non-dispatchable nature. As such, it is difficult to achieve high penetration of wind power in the grid. Large scale energy storage systems such as pumped-storage hydroelectricity may present a solution by storing wind power when it is in surplus and releasing that power when there is a disparity between supply and demand, usually caused by peaks in power usage.

This paper examines an energy mix for Ontario where base load was provided by nuclear (12 GWh) and the only other power available to the grid was supplied by the existing hydro infrastructure (7.8 GWh) and a tenfold increase in wind generation (10 GWh). This was modelled in MATLAB using historical power demand data for the province, along with historical wind generation data that was scaled to create a model for available wind power for the desired nameplate capacity. With this data and model in hand, an hourly power consumption mix was then generated and the instances were demand exceeded supply were analysed. Finally a model was then created to simulate a pumped-storage hydro system and it's ability to reduce the times when demand could not be satisfied.

The model demonstrated the energy mix specified satisfied over 99% of the total demand, and was able to meet demand over 96% of the time, with wind accounting for 13% of power consumed while nuclear and hydro accounted for 72% and 15% respectively. With the addition of the pumped-storage hydro system with a total capacity of 5.75 GWh and a storage capacity of 140 GWh the demand was satisfied over 99% of the time.

It was recommended that the pumped-storage hydro model be refined in order to determine the feasibility of such a storage system. Recommendations were also made to explore the integration of solar power into the energy mix to aid in satisfying summer peaks as well as exploring bio-gas plants and the effects of conservation and smart meters on demand.

Nomenclature

η_w Factor of wind nameplate capacity available
P_{wg} Generated wind power
P_{wa} 30% of nameplate wind capacity

I. Introduction

Shifting to renewable sources of power generation such as wind can pose many problems to grid operators. One such problem is the intermittent and non-dispatchable nature of many renewable sources of power such as wind. This greatly effects their reliability.

In this paper, a model simulating an energy mix for Ontario is outlined where nuclear is used to supply base load power, and daily fluctuations and peaks in demand are supplied by wind when available, followed by hydroelectricity. In order to accomplish this, a scalable model for available wind power was developed from existing data of wind power generated in Ontario.

From this model, data is extracted and analyzed at times when the energy mix cannot satisfy demand. A highly simplified model of pumped-storage hydro is then developed in order to determine whether it is worth exploring as a method of storing wind power available during off hours in order to satisfy peaks.

II. Background

In order to properly understand the model outlined in this paper, one must first be comfortable with the concepts of base load, peak load as well as intermittency and non-dispathability of many renewable energy power sources. Basic knowledge of grid storage solutions and wind turbine capacity are also important.

A. Base Load

Base load can be defined as the minimum load placed on the power grid over a given period of time. Put differently, given a period of time, base load demand is the amount of power that must always be provided to the grid. Some power sources are more appropriate for generating base load then others. These are sources that are generally not load-following (output cannot easily be changed), may have high fixed costs (from construction and installation) but have low marginal or variable costs (operation)[1].

Nuclear is an excellent example of a base load power source. Although some progress is being made with respect to altering the output of nuclear generators in an effort to allow for some load-following capabilities, nuclear generators are not considered to be load-following[2].

Base load for Ontario is approximately 12 GWh[3].

B. Daily Demand Fluctuations and Peak Load

Due to power usage trends of residential, commercial and industrial energy consumers and environmental considerations, demand for power can fluctuate greatly on a hourly, daily, monthly and even seasonal basis. The highest points of these fluctuations are called peaks. Over a given time period, the highest of these peaks is defined as peak load, the maximum amount of power required from the grid over said time period.

Unlike base load sources, generators used to manage daily fluctuations in demand must be able to easily change their output. Generally these sources have low fixed costs and high marginal or variable costs. Natural gas generators are a prime example of load following and peak load power sources[1].

Peak load for Ontario is approximately 27 GWh[4]. This includes the 12 GWh of base load.

C. Intermittent and Non-dispatchable Renewables

Many popular sources of renewable energy suffer from issues relating to intermittency and non-dispatchability[5]. Wind and solar, two of the most commonly used sources of renewable energy are particularly affected. The sun only shines during the day time, and is often obscured by clouds, while wind speeds change constantly. Both suffer from seasonal variations. This intermittency and non-dispatchability of wind and solar mean that they are not good sources of base load, or suitable for load-following applications. In simple terms, you have to take it when you can get it.

D. Wind Power Capacity and Intermittency

The maximum power output of a wind turbine is defined its as nameplate capacity. However due to the intermittent nature of wind power discussed above, wind turbines rarely operate at nameplate capacity. When the output of a wind turbine is averaged over a substantial period of time, a factor can be determined which represents the percentage of nameplate capacity generated by the turbine. This is called a capacity factor, which for wind is widely stated as being between 20% and 40%[6].

E. Hydro: the Best of Both Worlds

Hydroelectricity is an exception to many of these rules. Hydroelectric generators are dispatchable renewable sources of power that do not suffer from the same intermittency and non-dispatchability issues as other renewables. As such, they are appropriate for both base load and load-following applications.

F. Grid Energy Storage

An option available to grid operators to better take advantage of intermittent power sources such as wind is large scale storage. Since wind power is non-dispatchable, at times it is available when it is not needed. Often this power is not captured and therefore goes to waste. Large scale storage solutions attempt to capture this power and release it when needed.

One of the most popular methods of large scale power storage as well as the most efficient is pumped-storage hydroelectricity. The basic concept is that water is pumped up behind a dam where it is held until it is needed. Pumped storage operates between 70% and 85% efficiency. There is currently around 90 GWh of pumped-storage hydro in the world today with the largest plant accounting for approximately 2.8 GWh[7].

III. Model

A. Setup

MATLAB was used to construct a model of electricity generation in Ontario. The MATLAB code for the model is given in the Appendix. Two key data sets serve as the foundation of this model. The first is historical hourly demand data for Ontario for the past several years. For the purposes of the model this data is the demand that the theoretical energy mix aims to satisfy.

Fig. (1) illustrates the power demand on the Ontario power grid between May 2002 and February 2010. The 12 GWH of base load and peak load of 27 GWh in August 2006 are both visible. It is evident that demand varies considerably. The variations observable at this scale are a product of seasonal variation. When examining the demand data over a smaller period of time, for example a week as in Fig. (2), there is noticeable daily variation in demand. These variations represent the daily fluctuations and peaks, discussed in the background, that the wind and hydro power generators attempt to satisfy in this model.

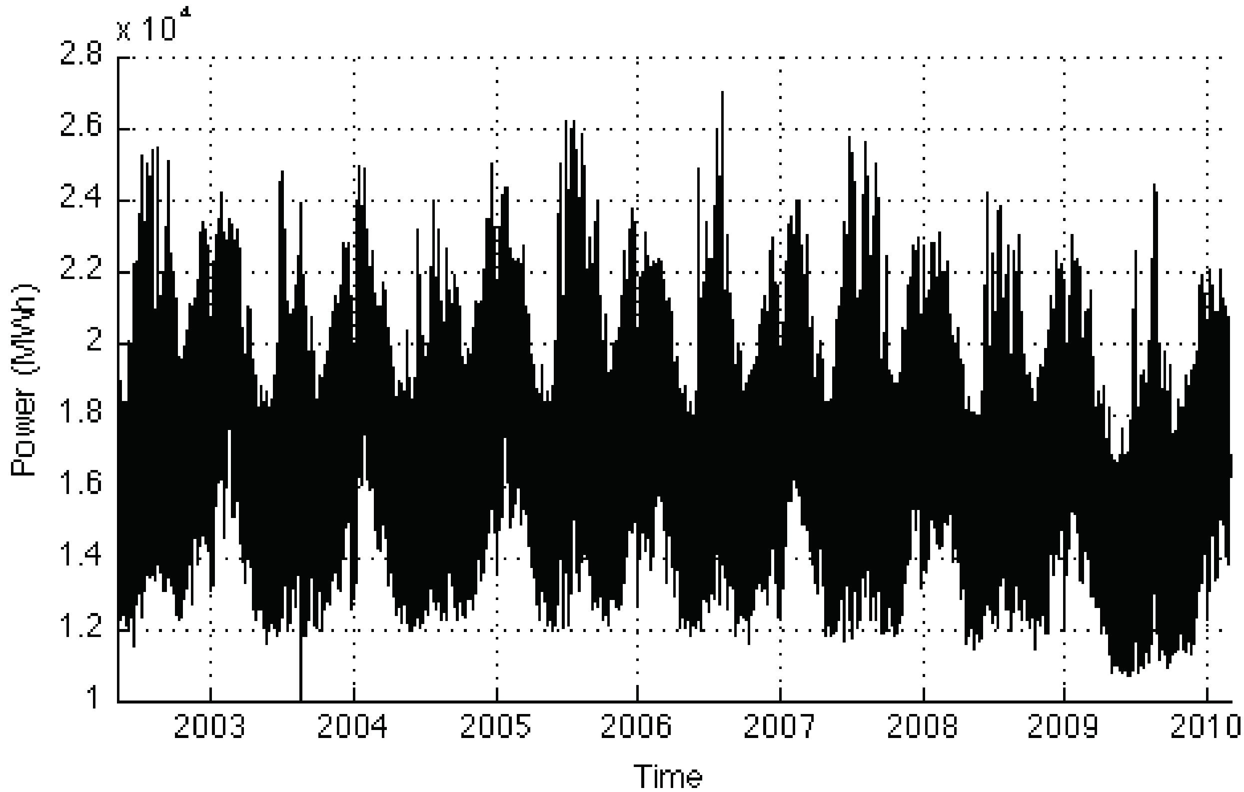

Figure 1. Houly Power Demand in Ontario May 2002 - Present[8]

1. Wind

The second data set vital to this model is historical hourly wind generator output data for Ontario, seen in Fig. (3). Again seasonal variation is evident. The intermittency of renewables such as wind power can be observed if the data is plotted over a shorter period of time (Fig. (4)).

The wind data was normalized to create a capacity independent model of wind power availability in Ontario. This was done as follows:

1. Nameplate wind capacity data for the province over the time span of the dataset was not available. As such, a linear trend line is calculated for the hourly wind generator output data which was assumed to represent 30% (capacity factor) of the nameplate wind generator capacity in the province at any point in time[6].

2. Each datapoint in the set was then divided by the value of the trend line at that time and multiplied by the capacity factor, for Eq. (1). This yielded a set of hourly factors representing the percentage of name plate wind generator capacity available.

$$\eta_w = 0.3\frac{P_{wg}}{P_{wa}} \tag{1}$$

These factors were then multiplied by a desired nameplate capacity for the province to create an hourly dataset simulating the amount of power from wind sources available on an hourly basis. The nameplate capacity selected for the model is 10 GWh which is approximately 10 times the current nameplate capacity of installed wind generators in the province[9].

It should be noted that this model is a crude simplification and assumes,

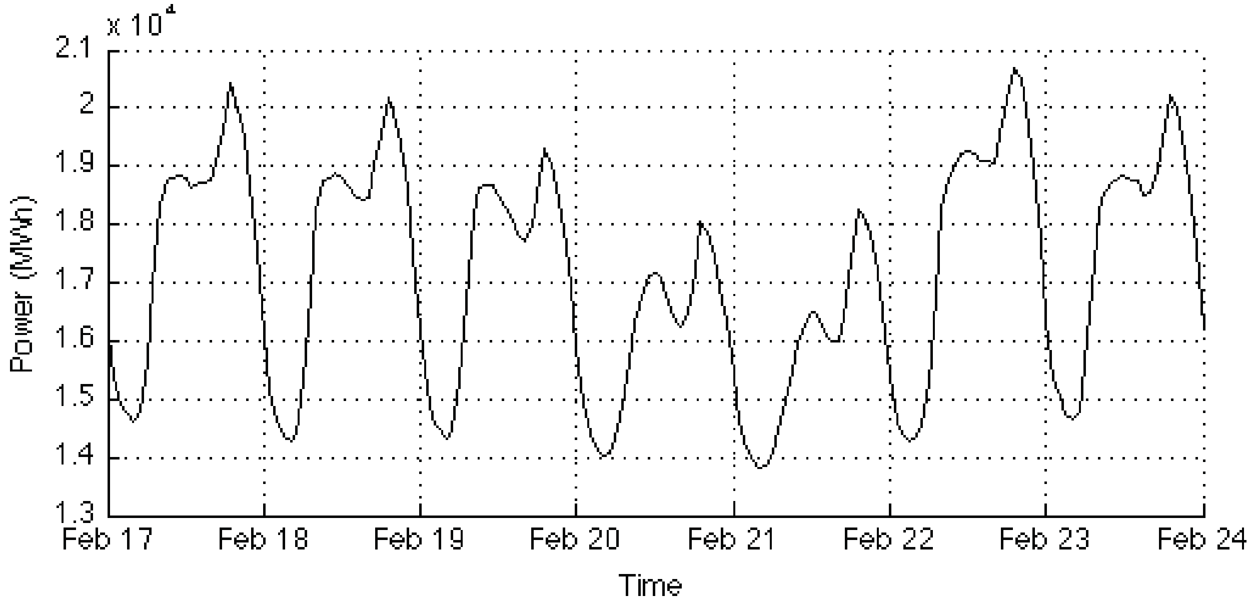

Figure 2. Hourly Power Demand in Ontario February 17th-23th 2010 [8]

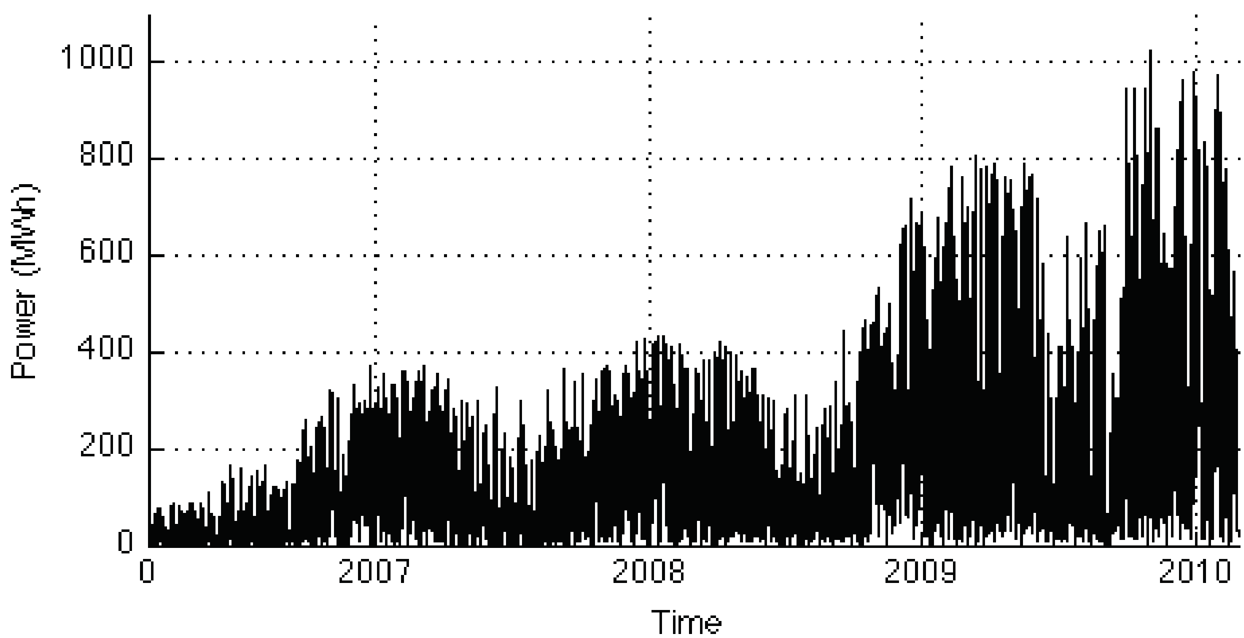

Figure 3. Hourly Wind Power Generated in Ontario March 2006 - February 2010 [8]

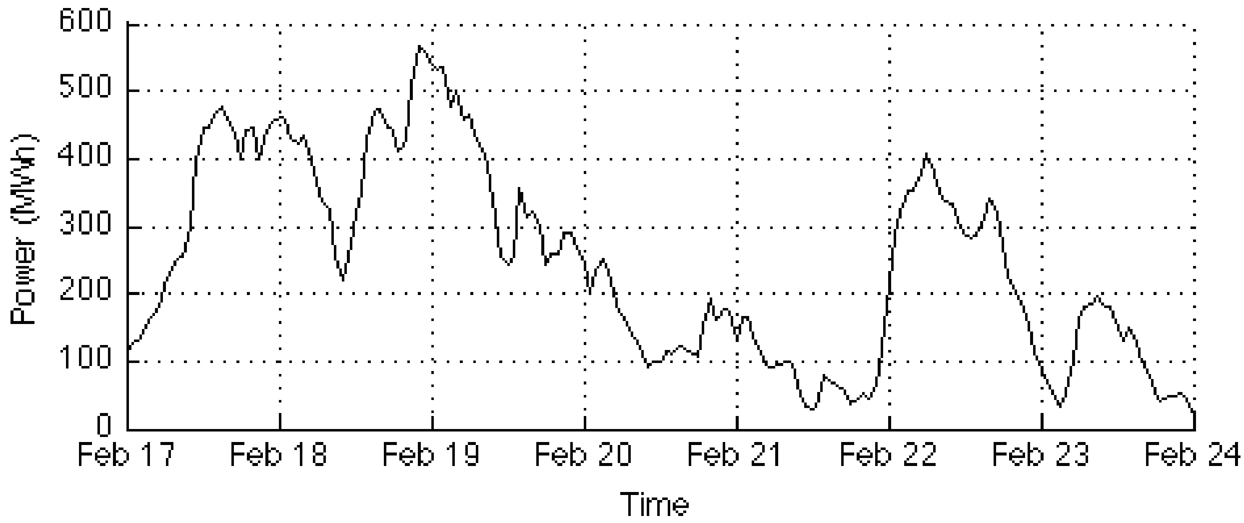

Figure 4. Hourly Wind Power Generated in Ontario February 17th-23th 2010[8]

1. wind power is always used by the grid when available;
2. current wind farms are distributed about the province in such away that their combined output represents a good approximation of wind available across Ontario; and
3. wind farms constructed to satisfy the increased nameplate capacity are distributed across the province such that the availability assumption holds.

2. Nuclear

In this model nuclear supplies base load for the province, as such, the model incorporates 12 GWh of nuclear power being generated over the entire data set. This is very close to the current nuclear capacity of the province[10]. For the purposes of this model, possible outages of nuclear power stations are not considered.

3. Hydro

For the purposes of the model, the hydro capacity is set to the current capacity of the province which is approximately 7.8 GWh[10]. Reservoir capacities of hydro dams in the province are assumed to be sufficient to provide the needed power in the model.

B. Simulation

1. Hourly Power Consumption

With the assumption that nuclear can provide base load, a dataset of hourly wind power available, a maximum capacity for hydroelectric power and a dataset of hourly demand to satisfy, it is then possible to simulate the hourly consumption mix of power generated over a specified period of time. This was done in the following manner,

1. at each hour, 12 GWh of nuclear power is added to the mix to supply base load to the system;
2. if there is still demand for power, wind power is added to the mix up to the total amount of available wind power; and
3. if there is still demand for power, hydroelectric power is added to the mix up to the maximum hydro capacity.

After the hourly consumption mix is generated, the demand that is not satisfied is quantified in two ways:

1. total demand not satisfied is expressed as a percentage of the total demand over the simulation period; and
2. the number of hours where demand is not satisfied is expressed as a percentage of the number of hours in the simulation.

2. *Pumped-storage Hydro*

Once the hourly power consumption mix is generated, it can be analyzed in order to determine the instances when demand is not satisfied. This unsatisfied demand is used as the draw on the storage system. Wind power that was available but not consumed due to low demand at the time, is used to charge the storage system. For the sake of simplicity, charge and discharge times of the system were assumed to be instantaneous.

The maximum discharge capacity of the storage is set to the maximum draw on the storage system (the largest value of unsatisfied demand from the hourly consumption mix) with a factor of safety of 10% (arbitrary). The maximum storage capacity is then set by assuming that the storage system should be able to maintain it's maximum discharge rate for 24 hours (arbitrary).

Finally the efficiency is set to 70% which is the minimum for pumped-storage hydro[7], and the storage system is assumed to be at full capacity at the start of the simulation.

IV. Results

A. Capacity Independent Wind Availability

Fig. (5) displays the wind power generated in Ontario since March 2006 along with a linear trend line simulating growth in capacity over that time. Although it is a crude approximation, the fact that the trend line slowly progresses to a maximum of approximately 300 MWh correlates well with the current actual installed nameplate capacity in Ontario which is approximately 1.0-1.1 GWh[11], for a capacity factor of 30%[6]. The result of normalizing the historical wind data can be seen in Fig. (6).

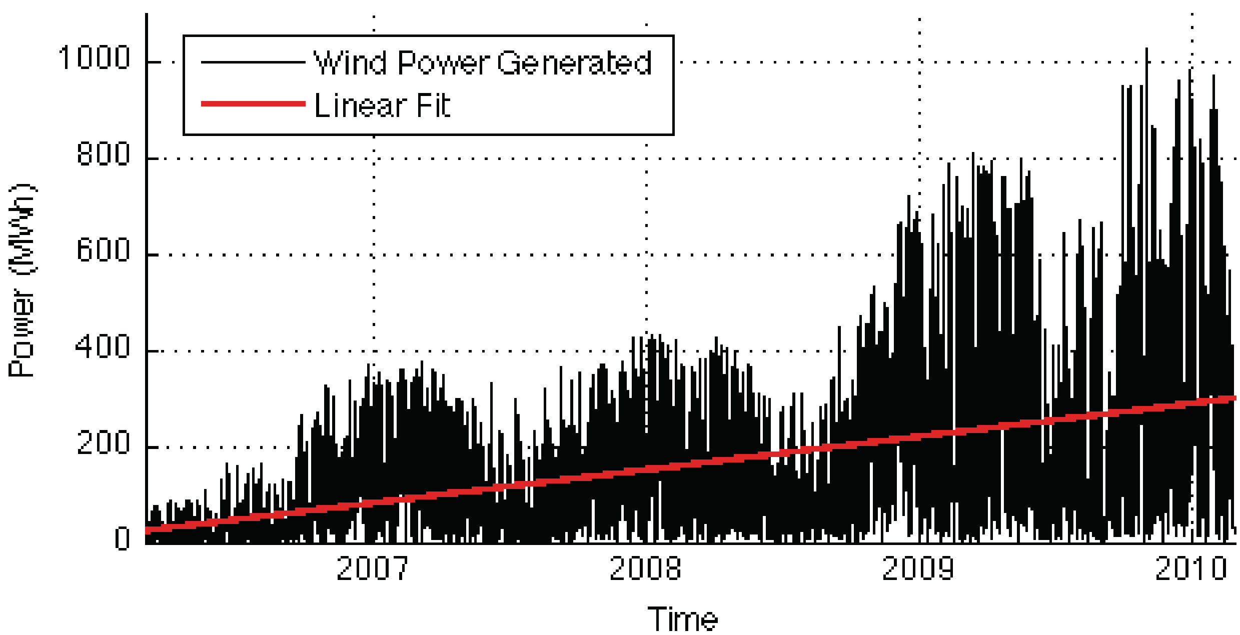

Figure 5. Hourly Wind Power Generated in Ontario March 2006 - February 2010 with Linear Trend Line

The normalized wind availability presents a problem. At the start of the graph, it can be observe that factors greater then one are common. It is not possible to generate more wind power then the nameplate capacity. Therefore, it was assumed that, since this data is extrapolated from the beginning of the hourly wind generator output data, it can be neglected since the nameplate capacity at that time is very small and therefore not an accurate representation of available wind power across the province. Consequently, simulations were only performed with data starting in June 2007 and onward.

It should be noted that there are still a few instances further in the dataset where factors greater the one appear. However, due to the small frequency at which they occur and their magnitude not being significantly greater then one, their effect on the overall analysis is deemed to be negligible.

B. Hourly Energy Mix

Fig. (7) shows the output of the simulation. It can be observed that the vast majority of demand is satisfied. However, there are many short but significant times when there is not enough power available to satisfy demand.

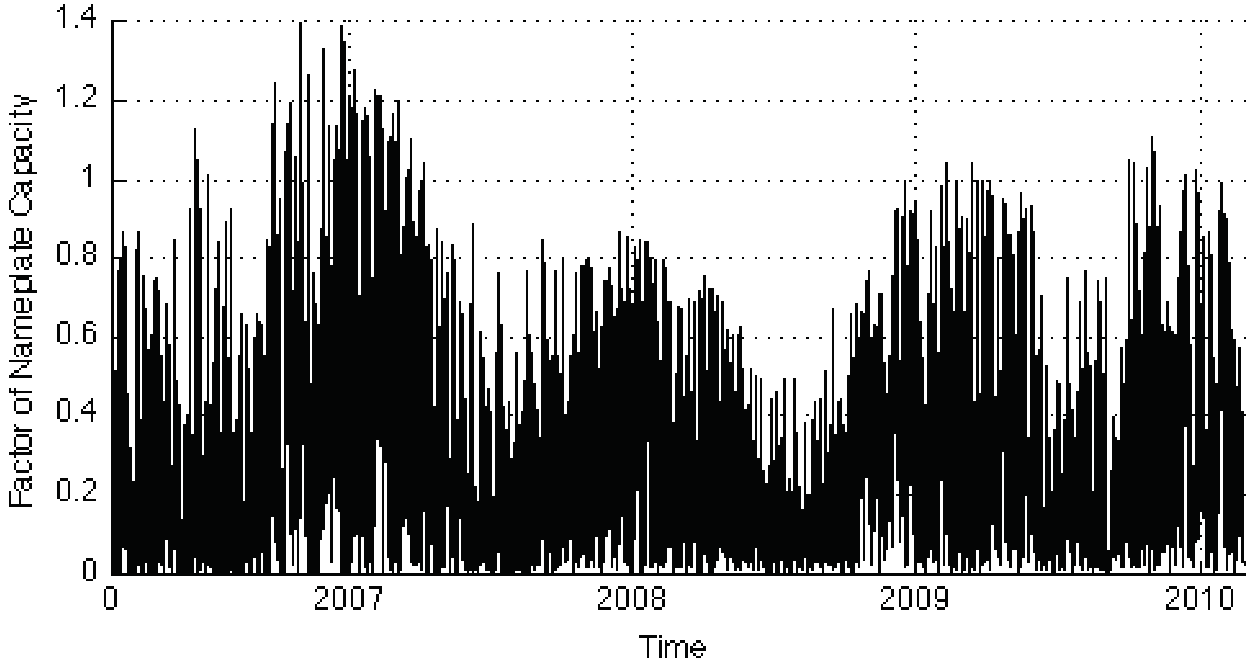

Figure 6. Hourly Capacity Independent Wind Availability in Ontario March 2006 - Present

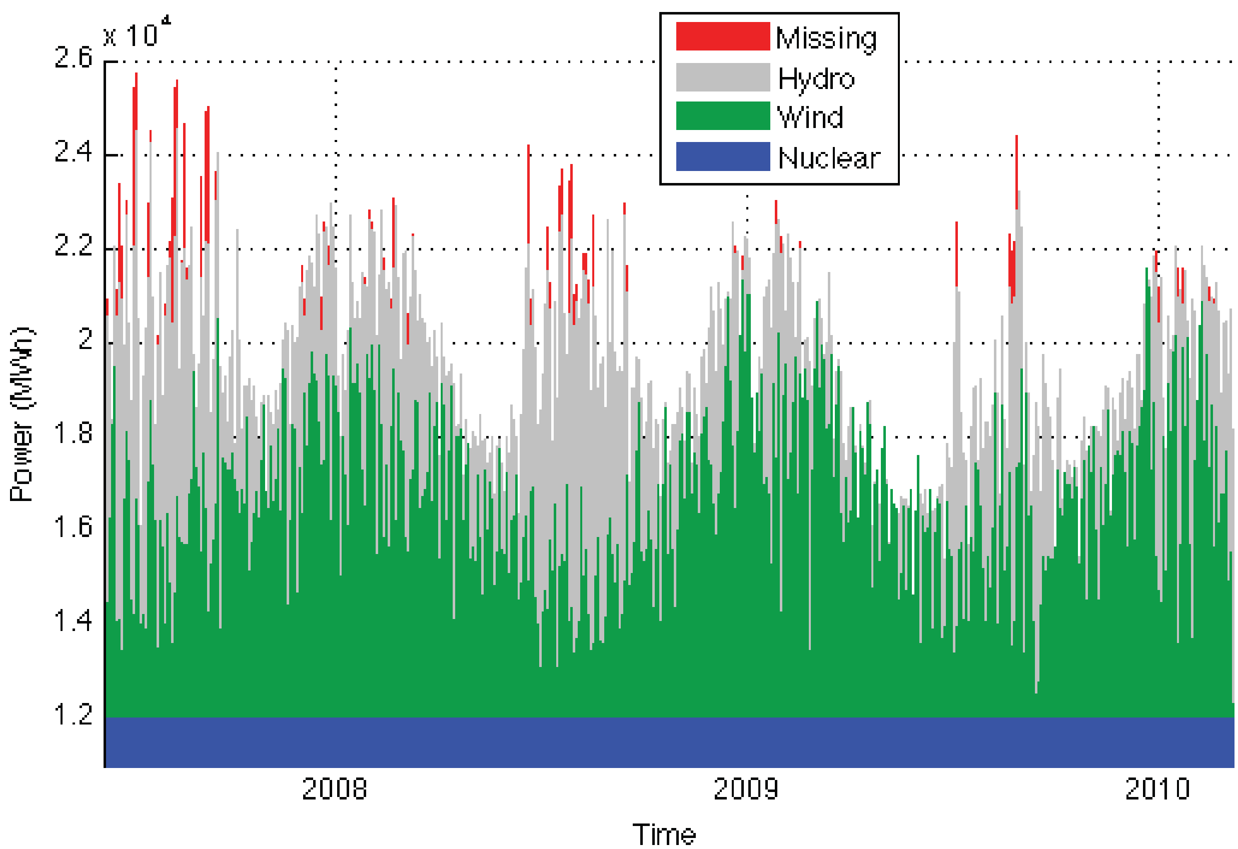

Figure 7. Simulated Hourly Power Consumption for Ontario June 2007 - February 2010

In Fig. (8), a close up of a five week period is plotted, where there are large peaks of unsatisfied demand. Examining the data more closely, it can be seen that the frequency of times when demand is not satisfied increases in the summer, which correlates with decreased wind power availability.

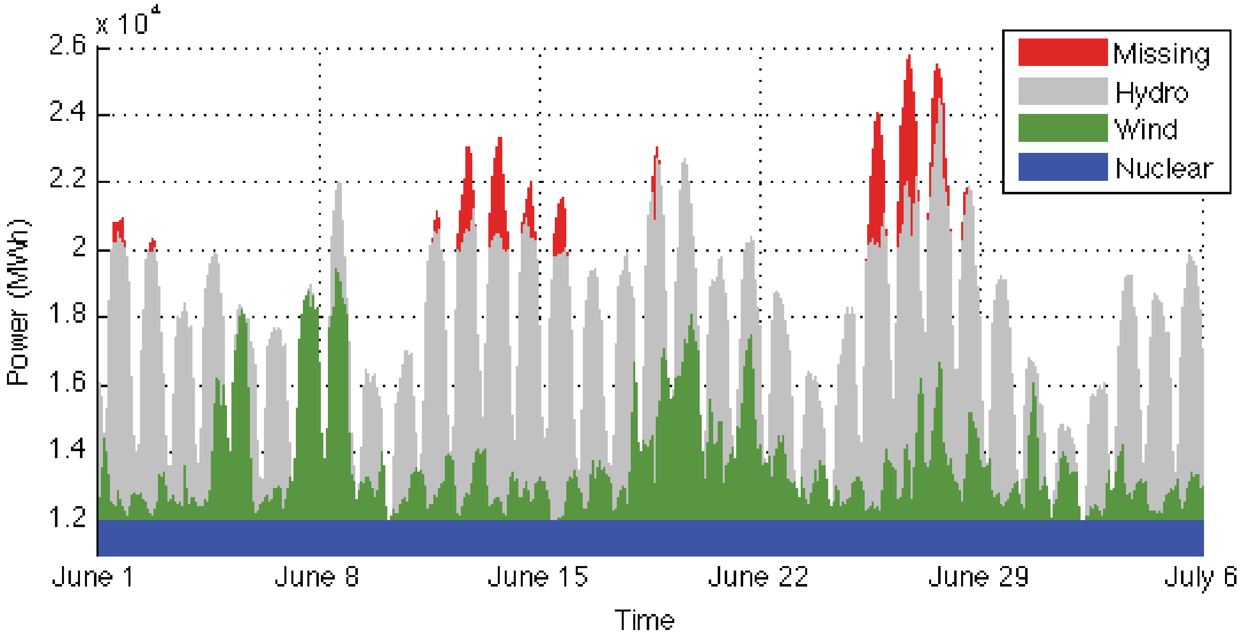

Figure 8. Simulated Hourly Power Consumption for Ontario June 1 2007 - July 6 2007

Shifting the attention from hourly consumption to total consumption over the entire time period reinforces the finding that demand not satisfied, less than 1% or 0.93 TWh, is minuscule in proportion the demand that is satisfied. Fig. (9) displays the breakdown of total power consumed.

Finally, of the 23,976 hours of demand simulated, there are 801 hours were demand is not satisfied. This represents 3.34% of the time in the simulation.

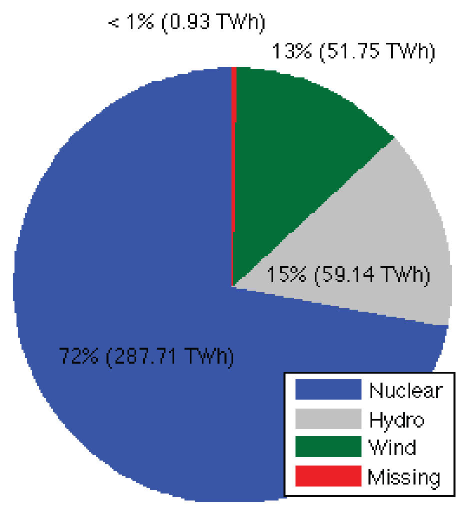

Figure 9. Simulated Total Power Consumption for Ontario June 2007 - February 2010

C. Storage Analysis

Summing all the available wind power that is not consumed in the simulation results in 15.44 TWh, which when compared to the 0.93 TWh of demand not satisfied appears to be rather large. However the distribution of the 0.93 TWh is very important. If there are many hours in close proximity were demand is not satisfied, the storage system may be depleted. This is evident in the results of the pumped-storage hydro simulation in Fig. (10), where the maximum discharge capacity of the storage system was calculated to be approximately 5.75 GWh and the total storage capacity to be approximately 140 GWh. Observing the plot, it can be seen that large peaks that are located close together have the ability to deplete the storage system.

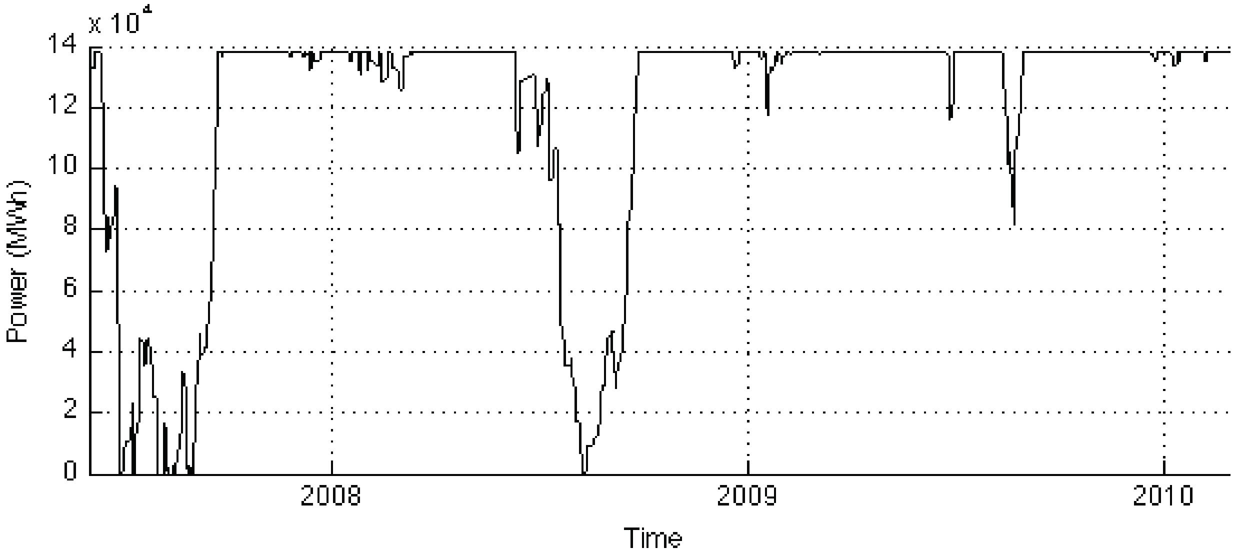

Figure 10. Simulated Hourly Wind Power Storage for Ontario June 2007 - Present

Apart from the summer of 2007, the storage system does quite well at providing power when needed in order to meet demand and was only ever depleted once. With the storage system, the amount of hours where demand was not satisfied decreased from 801 to 105 (7.6 times less) or 0.44% of the time. It should be noted that all but two of those hours are in the summer of 2007.

This model suggests that if a handful of pumped-storage hydro plants with a combined capacity of 5.75 GWh were constructed with their reservoirs able to store 140GWh combined, the province of Ontario could supply it's citizens with nuclear and renewable energy over 99.5% of the time using the energy mix specified. However, due to the simplicity of the model for pumped-storage hydro presented in this paper, conclusions relating to feasibility cannot be made.

The results do suggest though that further research is warranted.

V. Conclusions

- Increasing nameplate wind capacity in the province to 10 GWh enables wind to provide a sizeable contribution to the grid, 13% of overall power consumed in the simulation.
- Availability of wind power is reduced in the summer while peaks become greater at times creating a disparity between supply and demand.
- The mix of power sources adequately supplies the majority of demand in the simulation. Over 99% of the demand is satisfied by the combination of nuclear, wind and hydro.
- Using pumped-storage hydro as a means to store unused wind power in order to satisfy peaks warrants further research.

VI. Recommendations

- Refine the pumped-storage hydro model by accounting for reservoir filling times and perform calculations to determine rough reservoir sizes needed to accommodate the required amount of storage.
- Explore solar power as a means to help satisfy peaks in summer because peaks in the summer are likely correlated with high levels of solar insolation.
- Explore bio-gas as a renewable source to satisfy peaks.
- Incorporate existing natural gas plants into the model to handle unsatisfied peaks.
- Explore and incorporate load-balancing effects of conservation into the model.
- Explore load balancing methods such as smart meters.

- Refine the model to account for reservoir levels of hydro plants.
- Perform available wind analysis with actual nameplate capacity data rather then a trend line.

Appendix

A. MATLAB Code

```
%% Calculate Wind

wind.newCapacity = 10000;
wind.capacityFactor = 0.3;

for i = 1:size(wind.time,1)
    wind.factorOfNameplate(i,1) = wind.generated(i) / wind.trendLine(i) * wind.capacityFactor;
end

wind.newPower = wind.factorOfNameplate * wind.newCapacity;

clear i;


%% Create energyProduction

clear energyProduction

index = 10969; % start from June 2007

energyProduction.time(:,1) = wind.time( index:size(wind.time,1),1 );
energyProduction.time(:,2) = wind.time( index:size(wind.time,1),2 );
energyProduction.peak = 27000;
energyProduction.nuclearCapacity = 12000;
energyProduction.hydroCapacity = 7800;


%% Add Nuclear

energyProduction.nuclear( 1:size(energyProduction.time, 1), 1 ) = energyProduction.nuclearCapacity;


%% Add Wind

for i = 1:size( energyProduction.time, 1 )
    netPower = demand.power( size(demand.time,1) - size(energyProduction.time,1)-1+i ) ...
        - energyProduction.nuclear(i);
    if netPower < 0
        energyProduction.wind(i,1) = 0;
        energyProduction.extraWindPower(i,1) = wind.newPower(index-1+i);
    elseif netPower < wind.newPower(index-1+i)
        energyProduction.wind(i,1) = netPower;
        energyProduction.extraWindPower(i,1) = wind.newPower(index-1+i) - netPower;
    else
        energyProduction.wind(i,1) = wind.newPower(index-1+i);
        energyProduction.extraWindPower(i,1) = 0;
    end
end
```

```
clear i netPower;


%% Add Hydro

for i = 1:size( energyProduction.time, 1 )
    netPower = demand.power( size(demand.time,1) - size(energyProduction.time,1)-1+i )...
        - energyProduction.nuclear(i) - energyProduction.wind(i);
    if netPower < 0
        energyProduction.hydro(i,1) = 0;
        energyProduction.missing(i,1) = 0;
    elseif netPower < energyProduction.hydroCapacity
        energyProduction.hydro(i,1) = netPower;
        energyProduction.missing(i,1) = 0;
    else
        energyProduction.hydro(i,1) = energyProduction.hydroCapacity;
        energyProduction.missing(i,1) = netPower - energyProduction.hydroCapacity;
    end
end

clear i netPower;


%% Total Power Consumption (TWh)

totalPower.nuclear = sum(energyProduction.nuclear)*10^(-6);
totalPower.hydro   = sum(energyProduction.hydro)*10^(-6);
totalPower.wind    = sum(energyProduction.wind)*10^(-6);
totalPower.missing = sum(energyProduction.missing)*10^(-6);


%% Extra Wind

totalPower.windExtra = sum(energyProduction.extraWindPower)*10^(-6);


%% Stored Wind Power

clear storedPower;

storedPower.efficiency = 0.7;
storedPower.max = max(energyProduction.missing)*1.10*24;
storedPower.time = energyProduction.time;

storedPower.wind(1,1) = storedPower.max;


for i = 2:size( energyProduction.time, 1 )
        netPower = energyProduction.extraWindPower(i)*storedPower.efficiency ...
            + storedPower.wind(i-1) - energyProduction.missing(i);

        if netPower > 0
            if netPower < storedPower.max
                storedPower.wind(i,1) = netPower;
            else
                storedPower.wind(i,1) = storedPower.max;
```

```
            end
            storedPower.notAvailable(i,1) = 0;
        else
            storedPower.wind(i,1) = 0;
            storedPower.notAvailable(i,1) = netPower;
        end
end

clear i netPower;
```

References

[1]Booth, L. and Halpern, P., *Ontario Hydro at the Millennium: Has Monopoly's Moment Passed*, chap. Regulation of Transmission and Distribution Activities of Ontario Hydro, University of Toronto Faculty of Law, 1996, p. 77.

[2]"Growth Scenarios for UK Renewables Generation and Implications for Future Developement and Operation of Electricity Networks," Tech. rep., Sinclair Knight Merz, June 2008.

[3]Independent Electricity System Operator (IESO), "Demand Overview: http://www.ieso.ca/imoweb/media/md_demand.asp," Webpage, April 2010.

[4]Independent Electricity System Operator (IESO), "Ontraio Demand Peaks: http://www.ieso.ca/imoweb/media/md_peaks.asp," Webpage, April 2010.

[5]Gül, T. and Stenzel, T., "Variability of Wind Power and Other Renewables: Management Options and Strategies," Tech. rep., International Energy Agency, June 2005.

[6]Renewable Energy Research Laboratory University of Massachusetts at Amherst, "Wind Power: Capacity Factor, Intermittency, and what happens when the wind doesn't blow?" .

[7]Electricity Storage Association (ESA), "Pumped Hydro: http://www.electricitystorage.org/site/technologies/pumped_hydro/," Webpage, April 2009.

[8]Independent Electricity System Operator (IESO), "Market Data: http://www.ieso.ca/imoweb/marketdata/marketData.asp," Webpage, February 2010.

[9]Zandt, D. V., Freeman, L., Zhi, G., Piwko, R., Jordan, G., Miller, N., and Brower, M., "Ontario Wind Integration Study," Tech. rep., GE Power, October 2006.

[10]Independent Electricity System Operator (IESO), "Supply Overview: http://www.ieso.ca/imoweb/media/md_supply.asp," Webpage, April 2010.

[11]Independent Electricity System Operator (IESO), "http://reports.ieso.ca/public/GenOutputCapability/PUB_GenOutputCapability_20100411.xml," Webpage, April 2010.