The Windro Skyscraper: A Concept

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***Abstract*—Innovative integration of new technologies can benefit our society greatly. This paper presents a system which exploits the synergy of wind and hydro (windro) generation in an appropriate environment. The system presented is a pumped storage system integrated into a skyscraper to store wind power and deliver it at times of peak demand. A discussion is provided of why this is an appropriate environment. The benefits of the system include; increased value of the wind power, city centralised power generation and the smoothing of the building's electricity demand profile. An electrical model of the system is developed in PSCAD and results presented.**

***Index Terms*—**
Renewable Energy, Distributed Generation

I. Introduction

Innovative solutions for integrating emerging technologies can benefit the global community. By embracing emerging technologies and considering them in the design of modern systems, we can both nurture the technology itself and improve the overall system. Technologies such as new devices for power generation are becoming more prevalent with particular demand for wind, solar and geothermal power plants. The demand for renewable energy is driven by two main global factors; (i) The inevitable limit on fossil fuel resources on this planet, supported by predictions of peak oil production dating back to 1956 [1] and (ii) The contemporary proof of climate change [2], suggesting that emissions of carbon dioxide from combustion of fossil fuels are having a deleterious effect on our environment. These two factors have led to an increase in global research and general interest in renewable resources. These sources may be a viable, long term, alternative to fossil fuel based generation as they allow a sustainable approach to electricity generation. Due to the distributed nature of such resources this has sparked interest in distributed generation (DG) systems.

Wind turbines are currently being installed in ever increasing numbers around the world. However, one major disadvantage

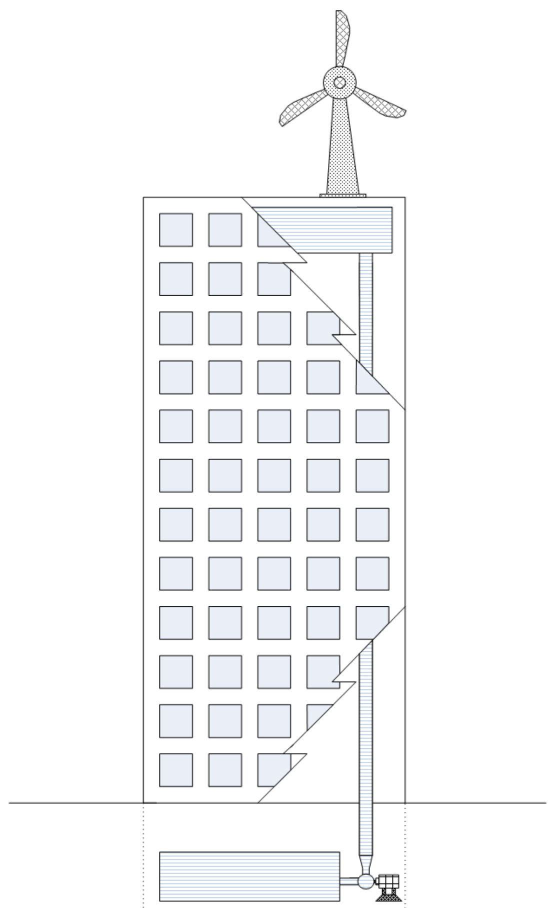

Figure 1. Conceptual Drawing of the Wind-Hydro System

to wind power is its intermittent nature and the implied need to maintain base load generating capacities, in the event of a reduction in wind power. In the event of a loss of wind there is a need to source all the power demanded from traditional power generators. Thus there can be no reduction in the traditional base load requirements of the system. This outcome is undesirable as the wind generators, whilst producing cleaner power, must still be considered to be non-dispatchable generators. The integration of pumped storage with wind power systems can help mitigate this phenomenon as the combination of wind and hydro electric generation provides flexibility in the scheduling of generation. Previous synergies of wind and hydro exist in installations including large hydro dams, small buildings and coupled systems with solar generation. Examples of these systems are presented in [3], [4] and [5] respectively. The combination of hydro with wind power allows us to shift the paradigm that wind is a non-dispatchable generator and create the idea that wind-hydro can be a semi-dispatchable, or short duration, dispatchable generation source.

This paper presents a synergy of wind and hydro generation integrated into a skyscraper. The pumped storage is utilised to store wind power overnight and deliver it at times of peak demand. Thus increasing the relative value of the wind power and providing it at times when it is required to offset local loads on the distribution system.

The paper begins with a description of the concept. Fig. 1 is provided as a visual depiction of the concept. This figure depicts a wind turbine on the top of a tall building with a pump installed in the basement of the building. Further the many benefits of the system are discussed in Section III including; centralised generation, heating and cooling impacts and smoothing building electricity demand. Finally a model of the system is developed in PSCAD and results are presented which demonstrate the operation of the "Windro Skyscraper".

II. The Concept

The concept of the Windro Skyscraper was originally developed as part of an entry to the Vestas Winnovation Challenge 2009. The Windro Skyscraper couples together a pumped storage system and wind generator to maximise the value of the wind energy. The installation of pumped storage increases the relative value of the wind power, by delivering it at peak times when it is of greater value. Thus making the wind power installation more financially viable. It is expected the system could potentially increase the incidence of wind power installations by making them more attractive to investors.

The quantity of wind power produced during the night is considerable. Unfortunately this power is of low monetary value due to the low demand during these hours. The Windro skyscraper uses this off-peak wind power to store water in a tank(s) using a bidirectional hydro generator / pump in the basement of the skyscraper. At peak demand times the water is released to produce power, flowing in the reverse direction through the hydro generator / pump. The rate at which power is needed to be produced during generation (peak demand) times can be calculated from the rate of power storage and the relative times of storage and production, as given by (1) and (2).

The overall cycle efficiency $(\eta_s \eta_p)$ encompasses the storage and production processes. The model used in this paper relies on the cycle efficiency assumed in [6]. In the pumped storage model, η_p is the efficiency of production (from water tank to grid), η_s is the efficiency of storing the energy (from electrical input power to water tank), E_p is the output energy produced and E_s is the initial input to the pumped storage. Note that this implies that the amount of water stored is governed by the actual stored energy given by $\eta_s E_s$.

$$\eta_p \eta_s E_s = E_p \tag{1}$$

$$P_{production} = \frac{\eta_p \eta_s P_{storage} t_{storage}}{t_{production}} \tag{2}$$

This paper presents an analysis of the electrical system involved in the development of the Windro Skyscraper. It is understood that the scale of the system will be heavily dependent on the relationship between building size, water elevation, structural limitations and capital cost. It is expected that the pumped storage system would not be retrofit to existing buildings, rather the system would need to be part of the initial structural design.

III. An Appropriate Environment

Now that the concept has been presented, this section provides a discussion on the relevant benefits of the synergy between wind and hydro generation implemented on a skyscraper. There are many ways in which masses of water can be used to improve a building's efficiency.

A. Harnessing the Wind

The location of the wind turbine on top of a building is not a new idea. The wind speed increases greatly with altitude, thus it is beneficial to locate a wind turbine on top of a tall building. New wind turbines have been designed to handle the turbulent air at this height such as those discussed in [7]. Further to this, placing a wind turbine in an urban area creates more viable wind farming land, as the entire CBD of a city may now be viable wind farming land. In the city environment the negative asthetic impacts of the wind turbine would also be decreased, as opposed to the situation in a natural landscape.

The construction of a wind-hydro system on a skyscraper would need to be considered in the initial building design.

Thus the cost of the initial installation and the reduction in the building power consumption over the usable life of the Windro system could be considered in the life cycle analysis of the building. The author of [8] notes the benefits of considering green options in initial building design. This system would indeed fit into the author of [8]'s suggested practice for green building design.

B. The Pumped Storage

The main limiting factor of pumped storage is the need to elevate the mass of water to store large amounts of energy. The relative potential energy of water can be calculated by (3).

$$E = mgh \tag{3}$$

Where E is the potential energy of the mass, m is the mass, g is the acceleration applied to a mass by gravity and h is the height of the mass. (3) shows that the energy potential varies linearly with height. This implies that either a very tall structure must be built or the size of the reservoir must be large to store a lot of energy. A hydro dam fits the later of these criteria and this is why there are many projects such as [3] coupling hydro dams with pumped storage. A skyscraper on the other hand fits the first criteria, it provides an existing platform for elevating masses of water. Due to the fact that a tall structure needs to be constructed for pumped storage, the cost of the structure becomes a limiting factor. The integration of pumped storage into a skyscraper provides an existing structure where the initial capital cost is an incremental increase in building cost, dependent on the weight of water to be stored. Whereas constructing a dedicated pumped storage tower results in large one off capital cost.

The placement of large masses of water in skyscrapers is already a requirement by law. For fire safety systems there must be guaranteed water pressure thus large masses of water must be placed in tall buildings [9]. Also there are existing water reticulation systems in large buildings to carry both fresh and waste water.

A viable option is to expand the capacity of the existing water storage tanks and set a minimum emergency tank fill level. This would also imply that most of the time, more than the minimum water, would be available in emergencies.

In hot and cold climates there is much scope for using the water ballast, pumped up over night, to act as a thermal ballast. One example of this is Hydro Place in Canada, it uses a central water ballast to improve the buildings heating and cooling profile [10]. The thermal ballast in the building could slow the heating of the building in the morning and there is potential for integration of this system with Heating, Ventilation and Air Conditioning (HVAC) systems. HVAC system designers are continually seeking to minimise the energy consumed by these systems, especially cooling loads such as air conditioning. One approach shown to minimise energy use is pre-chilling, described by [11], this provides further scope for the repeated use of the stored water.

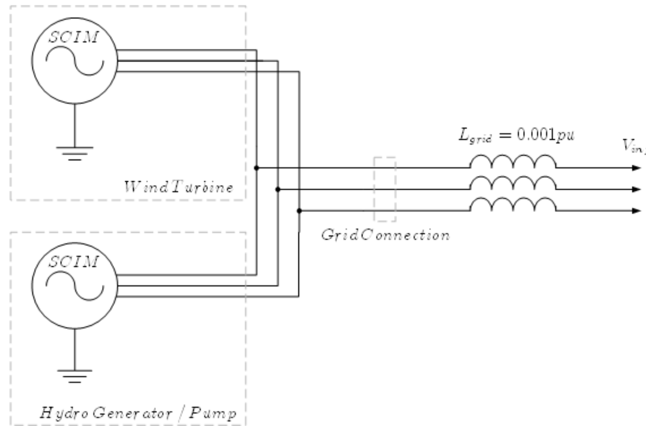

Figure 2. Electrical System

C. Energy Production

The distributed generation (DG) of electricity has two major benefits. It minimises transmission power losses and it creates more flexibility in the power system. The Windro system embodies both of these benefits as it would deliver power in the city centre with minimal transmission losses and could minimise the peak demand of the local area, by supplying more power in peak times [12]. If installed for example on a residential building the system may only serve to reduce the buildings energy consumption, the building may never export power to the grid, this leads to very low transmission losses as the power is consumed within the building.

The system relies on an electricity tariff structure that varies with demand, additionally the low transmission losses should also be considered in the evaluation of the value of produced energy.

IV. The Power Flow Model

A. PSCAD Simulations

The simulated electrical system is shown in Fig. 2. Two squirrel cage induction machines (SCIM) are coupled together directly. The per unit bases for the system are $S = 300\,kVA$ and $V_{ph} = 1\,kV$. The stiff grid voltage is modeled as a 10uH inductance coupled to an infinite bus.

The wind turbine parameters are configured to represent the SUT300 turbine produced by the "AutoControl Institute of ShenYang University of Technology". This turbine was selected

Table I
SUT300 WIND TURBINE SPECIFICATIONS

Parameter	Value (Units)
Cut in windspeed	3.5 (m/s)
Cut out windspeed	25 (m/s)
Rated windspeed	14 (m/s)
Shutdown windspeed	60 (m/s)
Lifetime	20 (yrs)
Nominal Output Voltage	400 (V)

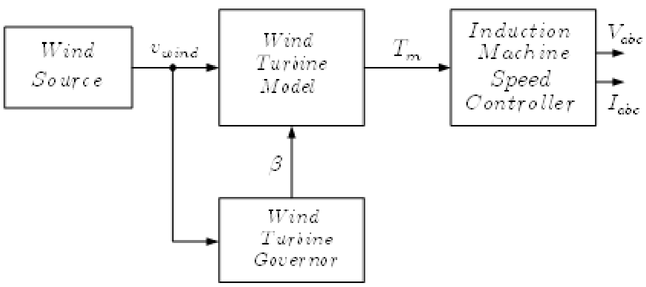

Figure 3. PSCAD Model

as the rated windspeeds and electrical configuration suited the application. The parameters used are shown in Table I. Calculations below, in (4) show the expected average windspeed to be around 12 m/s.

The wind turbine control scheme implemented in PSCAD is shown in Fig. 3. The wind turbine governor controls the pitch angle (β) to extract maximum power from the wind. The wind source model is based on the wind and air parameters presented in Table II. The wind turbine model's speed variation is based on both the average wind speed and a noise function added to produce the output observed in SCIM wind turbines. The pump is modeled as a SCIM with a constant torque load. It is expected that the mass of water to be lifted would apply a constant torque on the pump. This would be dependent on the mass of water in the pipe and the height of the reservoir.

The calculation of mean wind speed was based on [13] which

Table II
WIND AND AIR PARAMETERS FOR WIND SOURCE

Parameter	Value (Units)
Air Density	1.229 (kg/m^3)
Mean Wind Speed	12 (m/s)
Damping Time Constant	0.025 (s)
Noise Amplitude	0.7 (rad/s)
Surface Drag Coefficient	0.012
Turbulence scale	600 (m)

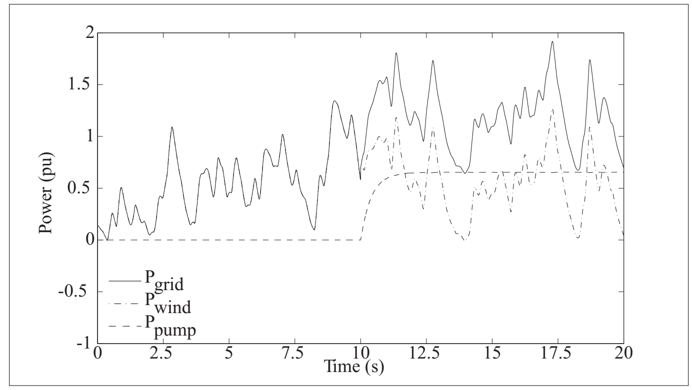

Figure 4. Power Output Transition

shows the average wind speed across Metropolitan Melbourne to be 6.3 m/s. The wind gradient can hence be calculated as in (4) giving a mean wind speed of approximately 12 m/s at a height of 100 m. Where the Hellman constant (α) is given as 0.27 for unstable air above human inhabited areas [14].

$$v_w(h) = v_{10}\left(\frac{h_w}{h_{10}}\right)^{\alpha} \tag{4}$$

V. RESULTS

A. PSCAD Simulation

Simulations were performed in PSCAD and results obtained for the system described in Section IV. PSCAD simulations were configured to run at 4 kHz and plots obtained at this sample density.

Fig. 4 gives a detailed view of the transition from pump off mode to power producing mode. The power exported to the grid with only a wind turbine is represented by P_{wind}, with the addition of the pumped storage system the output power is increased to P_{grid}. Also P_{pump} shows the power contributed by the hydro generator. It can seen that the average power delivered is much greater with the hydro generator incorporated into the system. The power producing mode to off mode transitions is also shown in Fig. 5.

Three phase grid voltages are shown in Fig. 6 before and after a transition in power production on the system. The per unit power production is shown in the lower two windows and the per unit voltage in the upper two windows.

Fig. 7 gives an example of a 300 second simulation run. This was observed to be approximately the maximum achievable simulation length. A number of such long simulation runs were concatenated to give a visual representation of longer operation periods, such as Fig 8 and 9.

Simulations were performed for the turn off and turn on of the generation mode and the turn on and off of the pumping

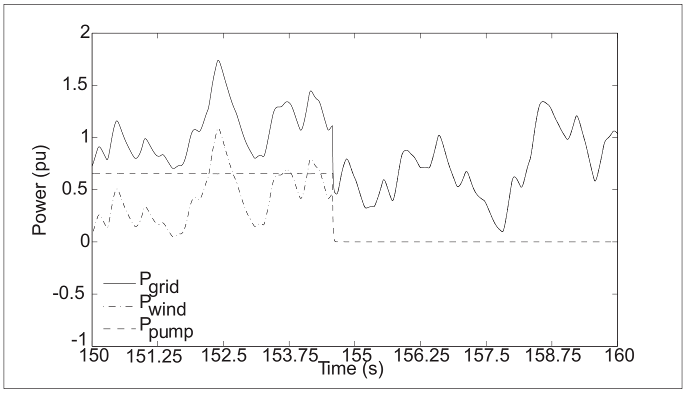

Figure 5. Pump to Off Mode Transition

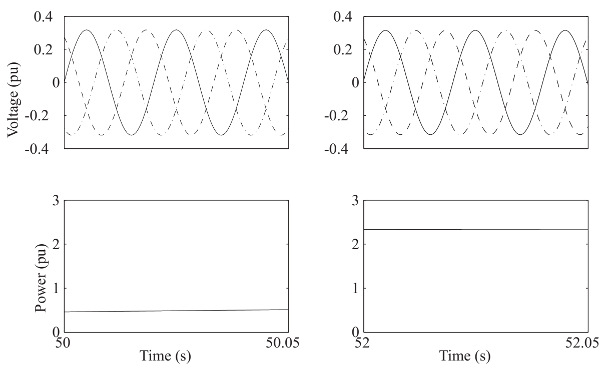

Figure 6. Three phase voltage before and after power transition

mode. These simulations were concatenated to give an example of a full day of operation, shown in Fig. 8. The power exported to the grid with only a wind turbine is represented by P_{wind}, with the addition of the pumped storage system a change in the output is observed to get P_{grid}. The pumped storage is configured to produce maximum profits by only storing power when it is cheapest in off peak times and only producing power when it is the most expensive. This is based on the "Time of Use" tariff structure for Energy Australia is given in [15] and provided in Table IV for reference.

The full day production graph (Fig. 8) was used to investigate the effect of the Windro skyscraper on a generic load profile. The load profile used is the generic load profile provided in the "HOMER" economic analysis software. This software provides a 24 hour load profile with 24 data points, one per hour segment. The load profile is scalable to any power demand with the peak demand scaled to 1 MW in this graph. Fig. 9 shows the effect of the Windro Skyscraper in reducing the average peak demand. On this graph, the load plot is the load profile obtained from

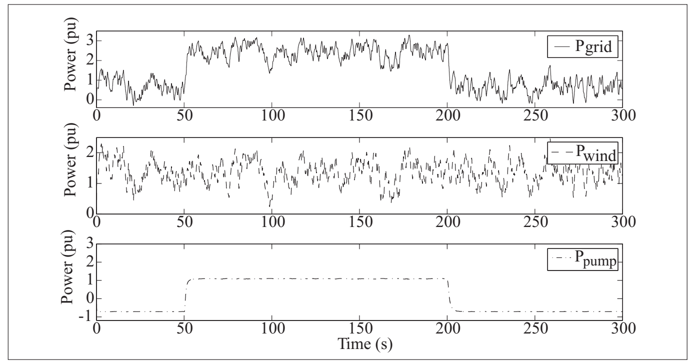

Figure 7. 300 Second Simulation Run

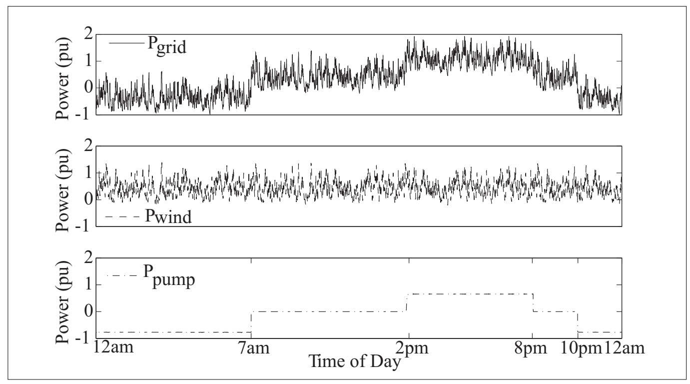

Figure 8. Full Day Production Graph

HOMER. Note the peak of 3.33 pu corresponds to a 1 MW peak, given the system base of $S = 300\,kVA$. The Windro plot ($P_{load+windro}$) shows the load profile minus the Windro output power. This plot represents the reduced load of the building and the peak demand is shown to be reduced from 1 MW (3.33pu) to 855 kW (2.85pu).

B. Basic Economic Analysis

A basic analysis of the increased cost of the power was performed again based on the"Time of Use" tariff structure for Energy Australia. Based on storage of energy only during off-peak hours and production only during peak hours we get $t_{storage} = 9\,hrs$ and $t_{production} = 6\,hrs$. From (2),

$$P_{production} = \frac{\eta_p \eta_s t_{storage}}{t_{production}} P_{storage} = 1.125 P_{storage}$$

This assumes a pumped storage cycle efficiency of 75% ($\eta_p \eta_s = 0.75$) obtained from [6]. The energy stored is worth $(9\,hrs \times 7.6\,\text{cents}) P_{stored}$ but the energy produced is worth $(6\,hrs \times 31.9\,\text{cents}) \eta_p \eta_s P_{stored}$. Considering a cycle efficiency of $\eta_p \eta_s = 0.75$, the gain in value is; $\frac{6 \times 31.9 \times 0.75}{9 \times 7.6} = 210\%$.

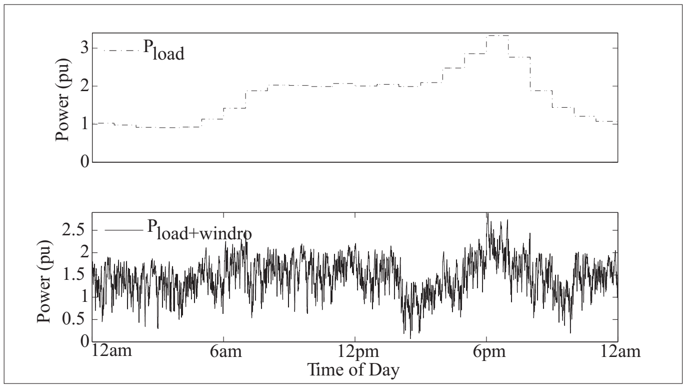

Figure 9. Effect On Load Profile

Table III
CYCLE EFFICIENCY VS ELECTRICITY VALUE

Cycle Efficiency $\eta_p \eta_s$ (%)	Increase in Electricity Value (%)
75	210
60	168
50	140
40	112

Table III shows the gain in value of the wind power for other lower cycle efficiencies.

It is clear that the achievable cycle efficiency of the pumped storage is strongly linked to the possible profits of the system. This concept was developed with the hope to drive further investment in wind by increasing the relative value of wind power. The analysis provided above indicates that an increase in relative value is achievable with the Windro Skyscraper.

VI. CONCLUSIONS

The concept developed in this paper utilised pumped storage to store wind power and deliver it at times of maximum demand. The Windro Skyscraper applies a wind-hydro synergy to an environment appropriate for pumped storage. The benefits of the system were presented including: the increased value of the wind power, city centralised generation of power and the reduction of the buildings peak electricity demand. A model of the electrical control system was developed in PSCAD and simulation results were presented showing operation of the system. The paper applied the PSCAD model to a typical load profile to demonstrate possible reductions in peak demand and also investigated the effect of variance in the assumed cycle efficiency on the increased worth of wind energy. This concept was developed with the hope to drive further investment in wind by increasing the relative value of wind power. The analysis provided above indicates that an increase in relative value is achievable with the Windro Skyscraper.

Table IV
ENERGY AUSTRALIA 'TIME OF USE' TARIFF STRUCTURE

Time	Rates Ex. GST (cents/kWh)	Time (Weekdays)
Peak	31.90	2 pm - 8 pm
Shoulder	12.90	7 am - 2pm & 8pm - 10pm
Off-Peak	7.60	10 pm - 7 am

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