When Intermittent Power Production Serves Transient Loads "The Art of the Possible"

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Abstract

The quote in the title, slightly severed from the original one [1], indicates our technical goal. We seek to ascertain what is possible in the short run regarding renewable power generation of notorious intermittence. To the intermittence add a load that varies daily and also seasonally. Another quote, of the same authorship: "When a man says he approves of something in principle, it means that he hasn't the slightest intention of putting it into practice" is cited as the opposite of our goal. The topic of renewable generation, storage and grid interfacing is complex in that it brings into one setting many diverse interests and technologies. We deem it impossible in a single study to establish the feasibility of such complex interactions. Yet, this is our long-term goal: that with studies as the one presented here, ways to profitably increase renewable generation will be found. In this paper, we focus on normal day for a grid operator, PJM, (Pennsylvania, New Jersey and Maryland). The variability of wind and (and assumed) solar outputs require a certain capability for load following or storage. Using dynamic modeling, we estimate the variability of the wind output and we simulate that of a projected solar penetration of 3% of new capacity. If the goal is to save for eventual use every unit of energy thus generated, a storage system must have the capability to levelize the supply of renewable power. Although levelizing is only one of many possible ways storage can be used, it is the one presented here. The capacity requirements for storage and generation of such a system are mapped out in 1 minute intervals, and shown in a histogram. This chart is useful to postulate minimum and maximum capacities for pumped hydroelectric storage (PS). Thus, the requirements placed upon turbine/pumps, their potential to serve the levelizing approach, and their response time to changing loads are established for the day under consideration. Knowledge of weather patterns may be helpful to plan dispatch and storage of renewable energy. The results of a brief excursion into the difficult topic of weather patterns are recorded here as well.

Keywords

storage of renewable energy, pumped storage hydro, wind variability, solar variability, wind autocorrelation.

[1] "Politics is the art of the possible", O. Von Bismarck.

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Introduction: The problem

To be useful, a power source must be controllable. This is so, because the daily electrical power load for any location is constantly changing. Consider for instance Fig 1, which shows the average electric load for the PJM grid for weekdays and weekend days [1]. The wind power input [2] into the grid is also shown for two consecutive days, on the vertical scale on the ordinate axis on the right side. The load profile varies with the hour of the day. Power grid operators such as PJM purchase generating power on a daily basis for the upcoming day. The bidding process by power generators specifies the hour of the day in which power generating capacity will be available. As demand unfolds the next day, different power assets retained by successful bidding are brought into line at specified times. Adjustments of required capacity, if necessary, are expensive whether positive or negative. The generation technologies that can respond within minutes to load changes can command premium prices, especially during the summer in locations where air conditioning loads define the peak yearly loads.

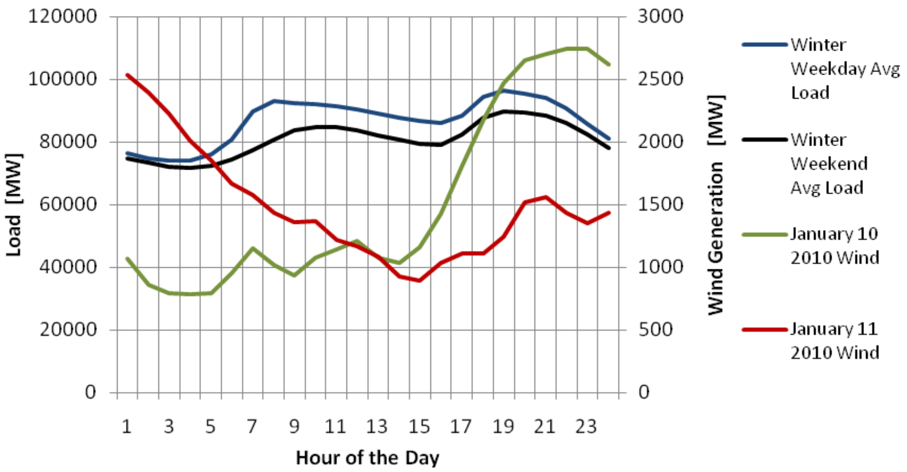


Fig 1. Load and wind generationprofile for the PJM service area, winter.

The bulk of the load is met with what is called "baseload generation", which is typically coal or nuclear based. When small load variations are present, "load following" power plants (hydro, steam or gas turbines) are brought into line, sequencing the higher efficiencies first. "Peak hours", when the load varies rapidly, are met with gas turbines or hydro. Unexpected increases are met with "spinning reserves". These reserves are ready to come on line within minutes. They can take several forms, such as a fired up coal plant and small steam turbine that is running at low capacity and in steady thermal regime. The turbine and generator can be loaded by increasing excitation and steam flow. Another type, generally regarded as more flexible, is the gas turbine: again, increasing the air, fuel and excitation can be done within seconds if the gas turbine is at temperature and synchronized, and only within minutes from a cold start. The third technology available is hydro power. Some Francis runners can be "motored" to spin in an air cavity, that can be flooded to produce power within seconds of demand. Grid operators meet demand with baseline, intermediate and peak hours power generation, as shown in Fig 2. Small, continuous load variations arising from small mismatches between load and supply require AGC (automatic generation control systems) that regulate the power production of mostly hydro or gas turbine units. The current wind generation in the PJM area is small, and its fluctuations , not different in principle than those of the load, are automatically handled via AGC. When AGC calls on fossil fuel technology, the benefits of renewable energy storage are lost.

The technologies that supply variable power tend to be expensive per unit of capacity. Gas turbines and hydro, as mentioned before, offer the capability of meeting peak loads and AGC. Small variations on the load may require continuous adjustment, as well as coordination with large industrial users. Both technologies are well suited to meet short-term changes in the load, which renders them quite unique with regards to the grid.

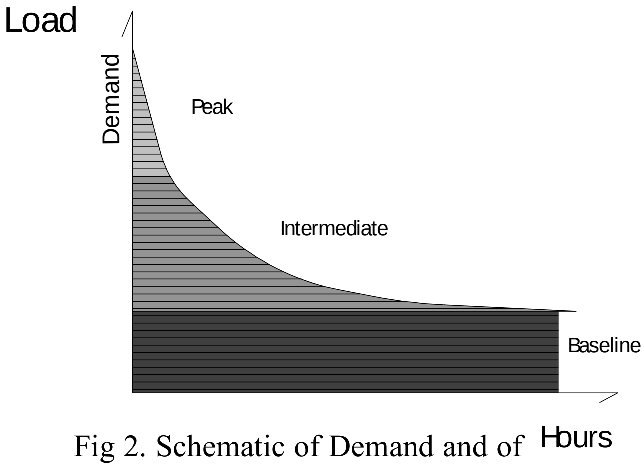


Fig 2. Schematic of Demand and of Demand Hours

In contrast, wind and solar power are not that easily regulated, because their supply is largely random, although weather correlations may allow some degree of predictability. Their intermittency is more conditioned by weather, season and time of day than any other technology. The random nature of the problem can be best appraised via Fig 3, where we display the wind and solar power production for a partly cloudy day. This summer day is selected because the renewable supply decreases as the load increases, although we do not consider the load for the purposes of the present study. Under ideal summer conditions, six 20 MW solar farms would peak at 120 MW of generation.

The renewable supply profiles are uncorrelated or not strongly correlated among themselves as discussed in the last section of this report. The load has variability of its own, as already discussed with reference to Fig 1. Therein lies the problem: at least in some days, it is impossible to fit the renewable production into any of the categories of Fig 2 during the whole day. The problem is compounded as we gaze into the future. Many states have enacted targets for renewable energy production meeting 20-30 % demand. In the PJM area, that comprises a wide geographical reach extending from parts of Ohio in the West to Maryland in the East, with an island in Chicago, over 50% of the proposed additional generation capacity in the next 20 yrs could be renewable, Fig 4.

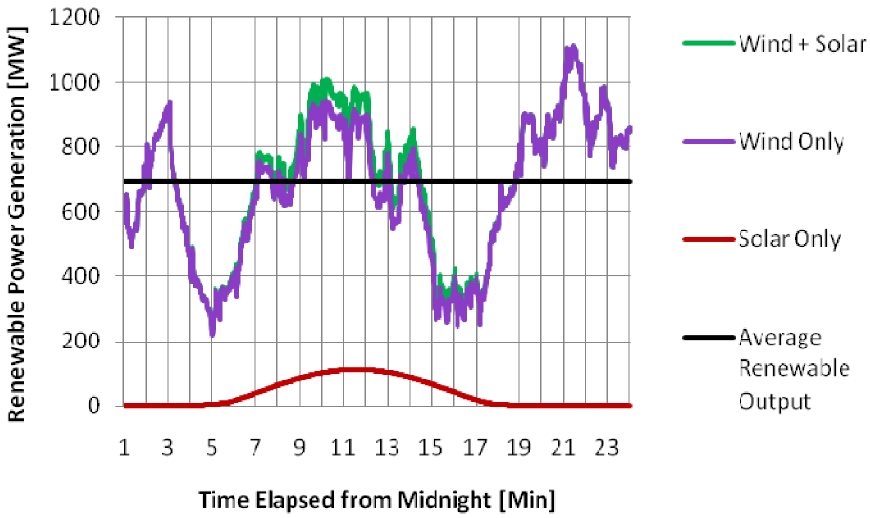


Fig 3. Wind and simulated solar penetration for the PJM service area, winter.

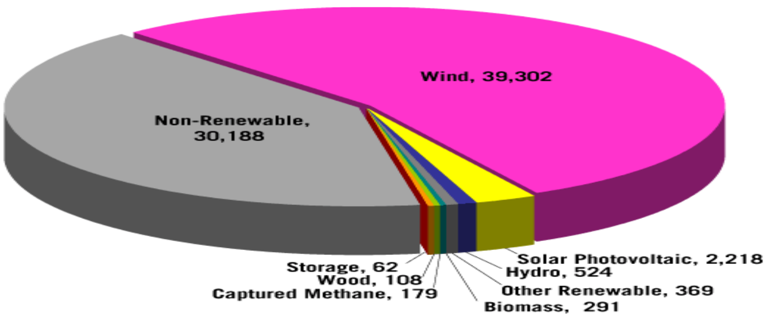


Fig 4. Projected energy mix for the PJM area, 20 yrs. [3]

This is a lofty goal, but we have some doubts about its realization. We seek with our tools to delineate ways to operate pumped hydro sotrage to maximize utilization of renewable energy. In this paper, we describe different ways whereby the existing (small) PJM renewable capacity could be levelized using PS.

Capacity and capacity value

Storage must erase, if only partially, the intermittency of renewables. Because of this intermittence, Independent Grid Operators (IGOs) have adopted rules whereby a capacity value is assigned to renewable and other forms of generation. Each plant has an installed capacity, but this is not the same as its capacity value.

The energy produced during the summer window by the resource (June 1st to August 31st, 4p.m. to 7 p.m.) is a measure of its availability [4]. The energy that could be produced if the resource were available all of the times of the summer window at full capacity is naturally a much larger value.

The ratio of the energy produced to the energy that could have been produced is the capacity value. For PJM, wind gets about 13% capacity value, whereas solar, more abundant in the summer, gets about 38% [4]. By comparison, the capacity value of thermal plants ranges from 70 to 90% [5], and that of some nuclear power plants can exceed 90%, although they may be coupled to PS in some locations. Increasing the capacity value of renewable energy would result in its increased profitability and penetration. Yet, it is not always clear how to increase these values. Two ways, not entirely independent, to deal with this problem are: to plan for suitable storage, or to improve weather prediction. The former results in the use of stored renewable energy when economic conditions warrant it. The latter may be helpful for the IGO to be able to call on all renewable resources first, thus avoiding the storage of renewable energy as this reduces its efficiency. The capacity value could increase if more renewable energy is purchased and injected in the grid during peak hours, and it will only be purchased in advance if its prediction is dependable. It may also lead the IGO to store excess renewable energy in some locations of large renewable penetration. In addition, accurate weather prediction may avoid the purchase of back-up excessive non-renewable capacity.

Ramp rates and how PS can help

The variability of load and of renewable generation defines the required storage capacity for a given application. A program to characterize load and power production variations has been written by the authors using VisSim software [6]. In the methodology adopted, “ramp rates” occupy a prominent place. For instance, ramp rates for the load profile are the change in demand over a given time interval. Similarly, ramp rates for renewable generation are the change in production for the same time interval. The value of ΔC (MW or GW) in Fig 5, is the ramp rate in T1. A different (larger) ramp rate, could be defined for T2.

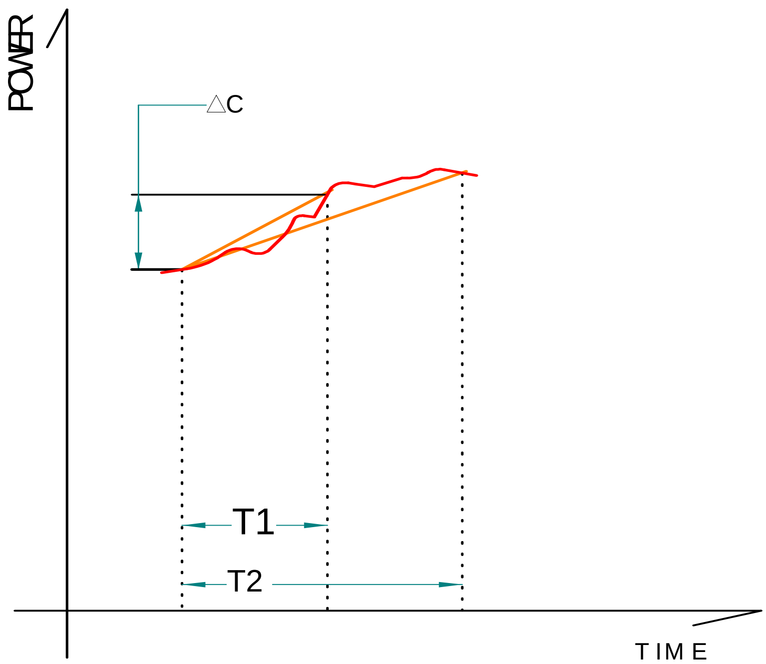


Fig 5. Ramp rate illustration

Data for hourly wind energy production in the PJM area are available [2]. Between hours, it is necessary to introduce plausible variations in the minute scale. The report by Wan [7], which covers four farms (ranging from 35-150 MW capacity) is adopted as reference. The report is useful for our purpose because it makes 1 minute interval wind power data available. We compare in Table 1 the 1-hr ramp rates for actual PJM data and for the Texas farms.

Table 1: Comparison of ramp rates for selected regions

	Maximum Hourly Ramp in 1 yr		Average 1 min. Ramp over 1 yr	
	Up	Down	Up	Down
PJM	27%	28.4%	3.6%	3.6%
Texas	26.9%	31%	3.8%	3.9%

Since the maximum and average ramps are quite similar as a percentage of installed capacity, it is decided to adopt for PJM similar minute to minute variations to those measured in Texas. A Cauchy distribution is randomly sampled to generate the fluctuations. The shape parameter of the Cauchy distribution is selected so that the minute to minute variations in wind power generation are similar to those observed in Texas by Wan [7]. A Cauchy distribution with gamma equal to 0.03 is then randomly sampled to generate the minute to minute wind power "fluctuations". As the end of the hour approaches, the location and shape parameters of the distribution are adjusted to force the hourly sum of the fluctuations to zero. In order to create the wind power output, these "fluctuations" are added to the wind power line resulting from the interpolation of the hourly PJM wind data. The modified wind farm output vs time , with a simulated solar input added, is shown in Fig 3. The assumed solar input is consistent in terms of proportion with the projections of Fig 4 regarding new generating capacity within the PJM region.

The solar input arises from the solar trajectory for the given day of the year, and from the extent of cloud cover. The solar trajectory can be determined for the given day of the year and for the farm geographical latitude, as a function of the solar hour, which is then synchronized with the wind data. If the cloud type, altitude and depth are known together with atmospheric moisture content, is it possible to estimate cloud transmittance [8]. Using then a clear sky model [9], the maximum radiation can be projected. For cloudy days, the clear sky model and cloud transmittance are used to estimate the direct and diffuse radiation reaching the ground. The radiation impinging in the collectors of the six 20 MW farms is the diffuse radiation plus the product of the direct radiation multiplied by the cosine of the incidence angle, which is a function of time. With the assumed cloud cover, about 65% of the incident energy is collected and transformed into electric power with an efficiency of 13% for the simulated day. Under these partly assumed generating conditions, PS could capture this wind and solar intermittent energy.

A PS plant

In a PS facility two different water reservoirs, separated by a suitable elevation, provide water for energy storage. Three variables define the capabilities of a PS plant, Fig 6. These variables are the net head, the mass of water stored and the water flow rate afforded by the machinery and penstock design. To a first degree, the storage capacity (kW-hr) is proportional to the product of the stored water mass and the elevation H. The generation capacity (kW) is proportional to the water mass flow rate and the elevation.

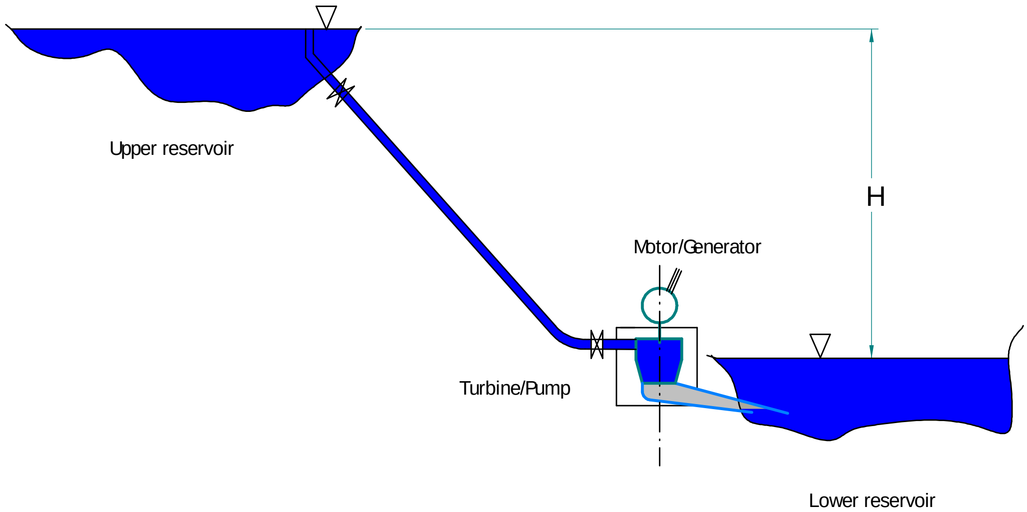


Fig 6. Schematic of a PS plant.

Similar considerations apply to the pumping capacity. The time available to displace the water mass (i.e. the water flow rate that one can design for) depends on the capacity of the smaller of the reservoirs.

The upper reservoir capacity typically limits the stored mass of water, and we assume this to be the case in the ensuing discussion. In conjunction with the head H , the flow rate from the upper to the lower reservoir dictates the turbine electric capacity. The head will vary between a maxium (MH) and a minimum level (mH). For a given flow rate, the generation time is maximized when generation starts at MH, and stops at mH. Generation cannot proceed when mH is reached. When the machine works as a pump to store energy, it can only operate for so long before the water level in the upper reservoir exceeds MH.

The determinant technology for energy storage (for the USA, at least) is the synchronous generators. In the pumping mode, these generators act as synchronous motors, whereby they work at the grid frequency. The pump capacity, in the absence of any bypass, is constant because its rotational speed is fixed.

In the turbine mode, partial loads down to 60 % of full load for Francis units are not uncommon. The response time of these units is short, in the order of minutes or fractions thereof. In the pump mode, capacity modulation requires special consideration. One solution is to have a large number of small impellers. Then, each can be activated as additional power becomes available, or deactivated when the power is absent. A less efficient arrangement consists of a bypass, whereby the pump operates at its single capacity, and a second pump/turbine uses the excess capacity to recover some of the pump power input. This is one way to regulate the pump capacity.
We attempt to capture the basics of the bypass regulation via Fig 7. We distinguish between electric power (rms voltage · current, corrected for power factor) and hydraulic power (mass flow ·

gravity constant · head). The net energy flow S into the upper reservoir is then the difference between the pump rated capacity and the bypass energy flow B , Fig 7. The input to the pump I is converted into S and B, with a pump efficiency. The energy stream directed to storage is S, and the bypass stream B flows through the turbine, and is converted to electric power at the turbine efficiency. This regulation arrangement is called for when the pump has a fixed capacity. Of course, variable speed motor/generators could come on board as the need for modulation becomes apparent due to increased reliance on renewable generation.

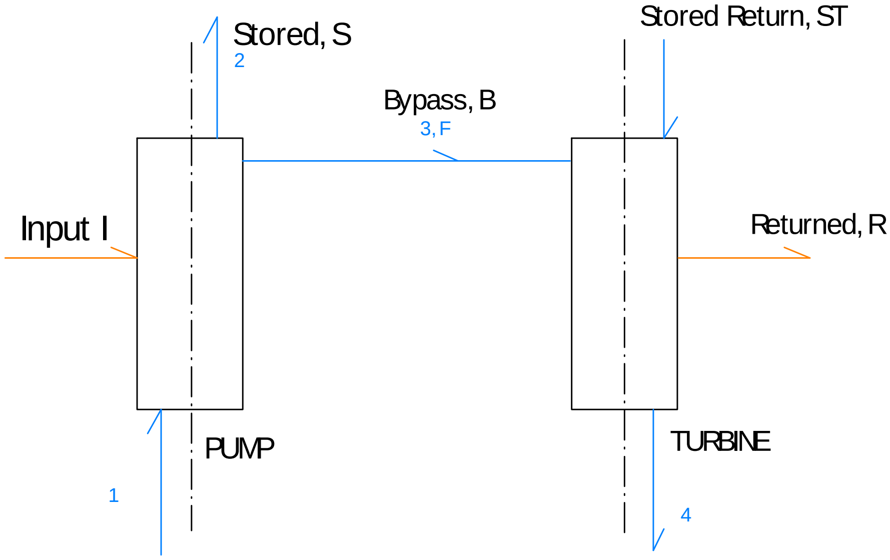


Fig 7. A pump at full capacity can partially discharge through a turbine

Levelizing operation

Clearly, storing all of the renewable energy when its generation exceeds the daily average generation, and selling it when the generation is below the average (this is, to produce a level supply during the day), is a possible way not to waste a single renewable kW-hr. Under this leveling scenario, the PS capacity can be assessed independently of the demand profile. The selected day under consideration for this exercise is analyzed for required capacities. The statistics developed in MathCad [10] allow the production of histograms of the required capacities, such as the one shown in Fig 8. Key data ensuing from Fig 8 are included in Table 2.

Table 2: Plant capacity and ramp rates for different time intervals

MW	Pump Mode	Power Gen Mode
Max Capacity	417	472
5’ max ramp rates	144	122
10’ max ramp rates	223	205

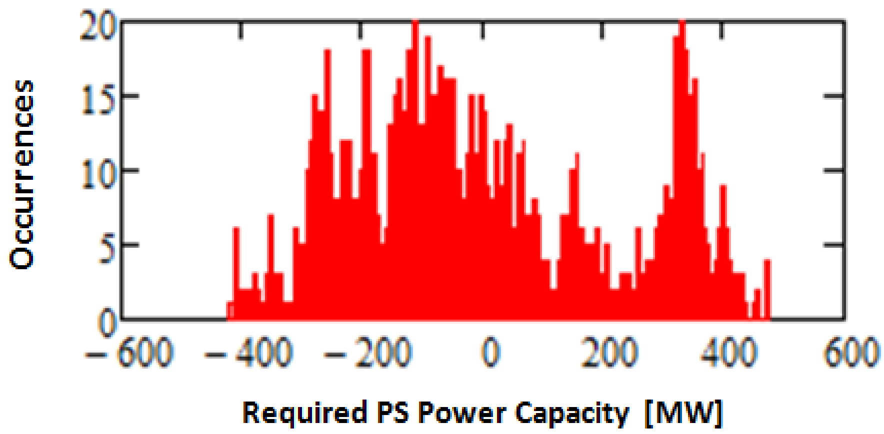


Fig 8. Histogram of required capacities for PHS, 1 minute intervals.
(Negative capacities denote pumping)

With the information from Table 2 and Fig 8, it is possible to estimate pump/turbine capacity to ensure levelizing of the renewable energy supply. Figure 8 does not reveal the sequence of generation or pumping capacities (the ramp rates bound these variations), but it does give an approximation of how often a certain pumping capacity will be required or how often a certain turbine capacity will be needed. A look at the negative range of the abscissas of Fig 8 reveals quite a multiplicity of pumping capacities. This fact poses problems since each pump has a set capacity.

The ramp rates indicate the adjustment in capacity for 5 min or for 10 min intervals. Clearly, it needs to be established if a PS plant can ramp up or down to negotiate a complete storage of renewable energy. The size of the grid and the mix of technologies available will also largely determine the size of the fluctuations that a PS plant must absorb or meet. Future work will further refine the ramp rates and the ability of hydro to meet them. At this point in our research, the ramp rates appear well within the capabilities of PS technology.

Figure 8 also serves as a base as to how to plan the capacity of pump/turbines for PS. After a thorough inspection of histograms is completed, it becomes necessary to specify the plant maximum and intermediate capacity ranges that can be met with a combination of impellers. Whereas the decision is ultimately an economic one, it is of interest to ascertain how the capacity ranges of Fig 8 can be met, without, at this point, studying how the ramp rates can be met. In the interest of simplification, we assume the wheels in turbine mode to have a constant efficiency ηt equal to 0.93 (the actual efficiencies are a function of the turbine loading). We also assume that Francis impellers can work down to a partial capacity of 0.6 of full capacity via wicket gate control. In the pump mode, the pump efficiency ηp is assumed to be 0.92, at one single speed and capacity. The motoring and generation electrical capacity define the ratio of capacities CR in pumping mode to turbine mode, assumed in this case equal to

$$CR = 0.88 \qquad (1)$$

For the conditions of Fig 8, to store and release every renewable kW-hr, one would need a range of (417-0) MW for pumping and (470-0) MW in generation. To obtain these operating ranges with acceptable efficiencies is difficult. For instance, consider a plant with N pump/turbine units.
When pumps are working at full capacity and turbines work with bypass flows as in Fig 7, an equation linking the pump and turbine capacities can be formulated. If the total pumping capacity TP needs to decrease to a fraction f, and there are n units in pump mode and m+p units in turbine mode, then is is possible to approximate the pumping capacity of the plant. The capacity on the LHS in the difference between the capacity of all the pumps (PC·n), minus the capacity absorbed by the turbines working at a fraction ξ of full load (TCM·m·ξ) or at minimum load (TCm·p):

$$TP \cdot f = PC \cdot n - TCM \cdot m \cdot \xi - TCm \cdot p \qquad (2)$$

with the constraints

$$\begin{aligned} & n + m + p \le N \\ & 1 \ge \xi \ge 0.6 \end{aligned} \qquad (3)$$

In Eq 2, it is assumed that all turbines operating at partial load do so at the same fraction ξ, which may not always be the case. With reference to Fig 7, the efficiency of the plant when simultaneous operation of turbine/pumps occurs and the stored energy is finally returned to the grid, (run around efficiency) is defined as *R/I,* which can be shown to equal the RHS of Eq 4:

$$\eta o = \frac{S \cdot \eta t \cdot (B / S + \eta e^2)}{I} \qquad (4)$$

where the constraint $B + S = I \cdot \eta p$ must be met. The loss into irreversibility (*I-R*) divided by the energy temporarily stored (S) measures the energy cost of storing energy, which we call the energy cost ratio *L:*

$$L = \frac{I - R}{S} = \frac{(1 - \eta o)}{S/I} \qquad (5)$$

The results of finding a few possible solutions for Eq (2) subject to constraints (3), are summarized in Table 3 below. The possible pumping ranges depend on the number of units. Meeting 1/16 of the pumping capacity is the smallest increment considered. When number of units failed to meet a larger capacity than 1/16, no further consideration was devoted to it. The difficulty in meeting a spectrum of pumping capacity arises when one turbine needs to run at low capacities to regulate the pumps. In the case of 8 pump/turbines needing to meet 1/16 capacity, this is not a real solution: the overall efficiency (with S=0.0625, B= 0.8575 and I=1) is high, namely 0.85. However, the cost ratio is 2.4, indicating that 2.4 units of energy are wasted when storing one unit.

Table 3. Regulation of pumping capacity.						
Capacity, S	Full	3/4	1/2	3/8	1/4	1/16
N=4	All pumps on	3 pumps on	2 pumps on	Unmet: 2 pumps 1 turbines ξ=0.44	x	x
N=6	All pumps on	Unmet: 5 pumps 1 turbine ξ=0.44	x	x	x	x
N=8	All pumps on	6 pumps on	4 pumps on	3 pumps on	2 pumps on	4 pumps 4 turbines on ξ=0.77 ηo=0.85 L=2.4

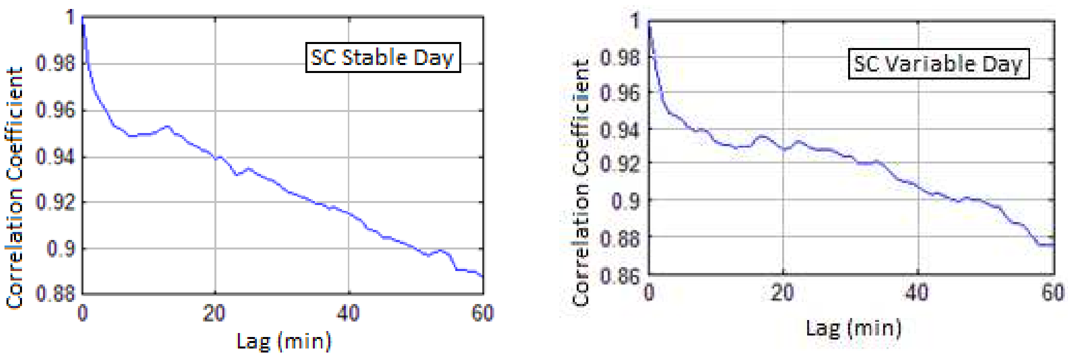
Clearly, eight pump turbines can meet a fine graduation of capacity. Still, it is possible to show that 4 pump/turbines alone, with a smaller pump turbine of 0.6 capacity of the other units, can meet virtually all generating capacities, and miss only a few pumping ones. Similarly, a plant of one pump/turbine (470 MW in turbine mode) and two turbine impeller wheels of 282 and 169 MW can cover the whole pump and turbine operating range, although the installation capacity will not be used constantly and low efficiencies will prevail at low capacities. It is certain that creative ways of combining turbine and pumps could lead to storage/generation at all capacities, albeit with reduced efficiency. Variable speed pumps are a great plus for renewable technology storage. PS plants that can operate with high efficiencies at part-load are also most desirable.

Those two approaches to capacity control (variable speed and part load) have been implemented in Europe. Ingram [11] reports that the 1060 MW PS plant in Goldisthal features two synchronous and two variable speed (asynchronous) pumps. The pump rotational speed variation ranges from 90 to 104 % of design. This range allows operation at better efficiency and part load control. Amler [12] describes three technologies to control pump capacity. In one, Pelton wheels are used to regulate a pump (much as in Fig 7, but the pump and the turbine not reversible). Because Pelton wheels have reasonable efficiencies at part loads, they can absorb excess pump energy and return power to the grid more economically than reversible Francis units could. KOPS 2 in Austria is an example of direct coupling of 180 MW Pelton turbines with 3 stage pumps, achieving 100 % power regulation. The reversible pump/turbine using Francis wheels is listed as a possible technology, with the drawback that reversing each unit takes time (up to ½ hr is our understanding). This time is necessary to reduce the speed, cool the unit and restart it in reverse, while avoiding water hammer. The variable speed technology of Goldisthal is also described, and one additional advantage mentioned consists of increased head operating ratio for pump mode (from 1 to 1.45). The Kops 2 project is impressively described in a technical brochure by Illwerke [13].

What about the weather?

While to tackle with minimum resources a problem of proverbial unpredictability is at the least adventurous, we have attempted such a task. We submit what conclusions we deem of value, although we note that a great deal of work in this area is in progress. The eventual results somehow must be brought together in some coherent form, useful for the dispatching and trading of electrical power. Our results are the product of applying simple statistical tools in an attempt to establish what can be reasonably predicted and over what span of time. We explored wind and solar energy both individually and together. We focused on three locations: State College (SC), PA, Desert Rock (DR) NV, and Elizabeth City, (EC) NC. Data sets were downloaded from the SURFRAD [14] and CONFRRM [15] websites. Wind data solar data were available at 1 and 5 min intervals, depending on location. A large number of Fourier power spectrums and cross and autocorrelations were completed in [16]. A limited set of results is shown here for the reader to appraise the reach of our conclusions.

In Fig 9 a and b, we show the autocorrelations of wind data over 60 min in SC. In Fig 9.a is a day with fewer and less intense wind shifting than in Fig 9.b. Both autocorrelations show that 20 min short-term predictions could have correlations of 93% or better. If additional information such as weather front displacement is incorporated in forecasting, the accuracy would improve over that of the autocorrelation.

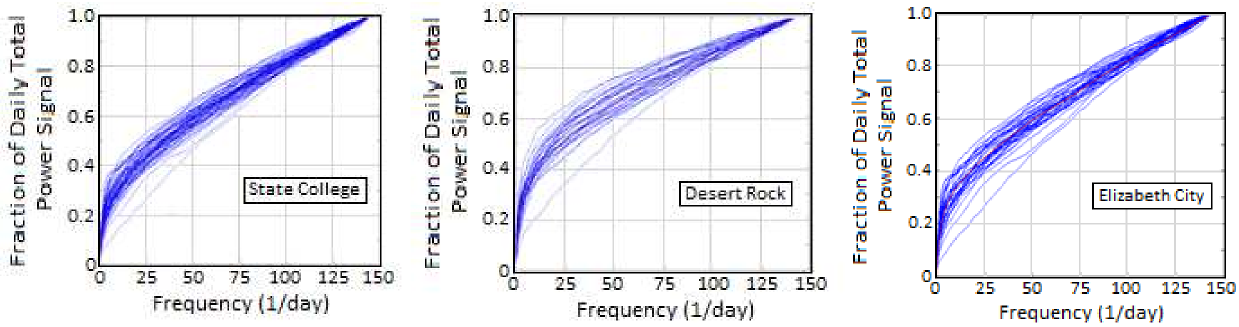


(a) (b)

Fig 9. Wind data (1’ data) autocorrelation over 60’ (a) stable day, (b) variable day.

It is noteworthy from Fig 9 that 10 min correlations are in the order of 95% for both days, and hence allow a rather reliable prediction over short term intervals. For longer time spans, including data such as expected weather front changes may allow a closer bracketing of wind variability.

When the wind data over long intervals are the object of an FFT, a possible interpretation is that the energy present at each frequency could (or should) be harvested. Naturally, the wind turbine would have to be capable of availing itself of all power in each frequency, a feat not always possible. Yet, over 24 hours, our analysis (limited by the Nyquist criteria) allows frequency definitions of up to 140 times/day (A visual inspection of the FFT results allow us to anticipate that the energy content in the wind is small beyond the peak frequency of 140 times/day). Energy content vs frequency plots are shown for SC, DS and EC for all the days of 2009 in Fig 10. (But only ½ yr for DR). The similarities within each location are surprising, indicating the 90% of the energy in the wind is contained in frequencies below 110-120 times per day. More importantly, DR shows that 50 to 70 % of the total energy in the wind over ½ yr will vary less than fifty 50 times a day or fewer. The variability will be smaller in the other two locations. The user can then plan for bounds as to what percentage of energy can be depended upon over one day, and how many times in the day substantial variations can be expected.

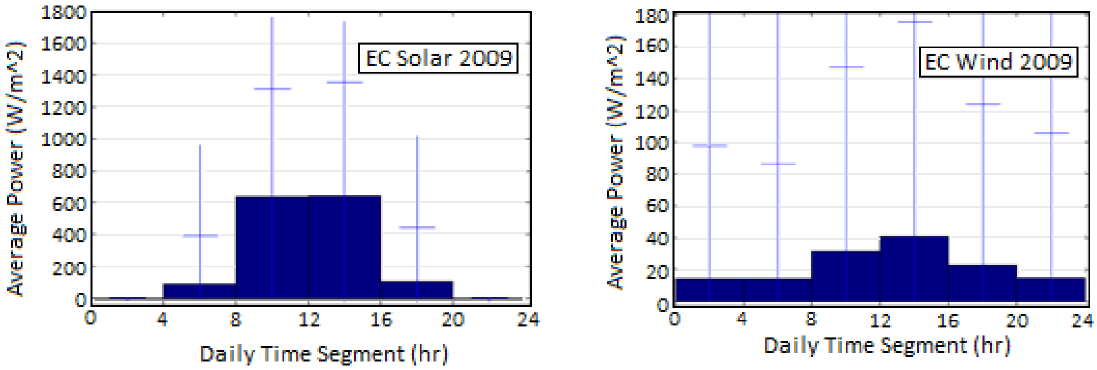


SC DR EC

Fig 10. Cumulative energy plots over 1 yr (or ½ yr, DR) vs frequency.

Cross correlations between wind and solar power could yield useful information for the purposes of energy storage. Short-term data is the only possibility to render these correlations of use for our intended purpose, namely to decide whether to store energy or to let it flow to the grid. Yet, short term solar-wind correlations, if they exist, are highly location specific [17, Exhibit 4-18] and do not seem to afford any predictability for our data sets. Long-term data are more amenable to broad correlation [16]. Histograms showing the solar or wind power available within given hours of the day for long time periods seem to exhibit some significance. For instance, we show in Fig 11 for EC that as the sun power increases during the day, the surface wind increases with some some time lag. The histograms are yearly averages, and standard deviations and maximum values for each time bin are included. When hurricanes are present, the wind energy values go off the chart scales. Clearly, surface data tend to show that wind and solar increase in this location during day light hours.

Similar trends were detected for SC and DR. Naturally, wind is of interest at higher altitudes. Yearly data for one location (80 m altitude, [17]) show peaks at sundown and sunrise. Our data are of interest in that detectable trends emerge, and may be of use for small wind turbines in conjunction with solar PV.



(a) (b)

Fig 11. Solar (a) and wind (b) histograms showing the yearly average power available at different hours of the day.

Conclusions

The intermittence of the current level of PJM renewable input to the grid is handled via AGC, storage and load following. Levelizing the renewable supply will improve its capacity value, although the financial aspects remain difficult to ascertain. The variable power PS technology is a feasible way to meet large capacities, but not small pumping or generating ones. Great strides have been made in Europe in terms of PS but direct coupling of turbines and pumps and by variable speed pumps and turbines, but their application in the US remains elusive.

Reaching a level supply for our selected day in the PJM domain is not straightforward. This operation would require a continuous spectrum of pumping and generating capacities, requiring either pump regulation using turbines, or variable speed pumps. When regulation is considered using reversible Francis wheels at constant rotational speed, the efficiencies to store and retrieve energy can be rather low. Whereas we recognize here that levelizing the supply may not be the best strategy, it is one way to store and use every renewable kW-hr. However, limitations on how fast pumps and turbines can be reversed make this operation difficult, unless extra capacity is built into the system and some of the equipment is accepted to be idle some of the time. In a way, levelizing may be the most difficult goal concerning renewable storage and dispatch.

Other strategies will be studied in future work, namely that of storing whenever surplus renewable energy can be purchased, and selling it during peak times. A continuous decision-making over a time horizon of a few hours may also result in worthwhile conclusions regarding capacity and ramp rates to be met by a PS plant.

Our brief excursion into the weather was fruitful, in that it shows that both short and long term predictions are possible for energy harvesting and storing. More importantly, the analysis binds the accuracy of such predictions: short term correlations factoring in weather fronts and other major changes can be useful. In addition, the frequency of variation of significant wind energy components can be ascertained and it is historically bounded, at least for the three locations considered. The historical data of Fig 10 shows the maximum variability that desired energy contents may exhibit over a year. Long term correlations, as shown in Fig 11, establish a weak link between solar and wind at the ground level. The weakness is such that application of such cross correlation is probably not warranted, unless a great number of renewable physical locations over a widespread area contribute to the supply.

Nomenclature

B	bypass energy for a pump input of one unit of energy
CR	capacity ratio
f	fraction of total pumping capacity
I	energy input to pump motor [MW-hr]
L	energy storage cost ratio
m	number of units in generating mode at full or partial capacity above minimum
n	number of units in pumping mode
N	total number of units
p	number of units in minimum capacity generating mode.
PC	Pumping capacity of each unit [MW]
R	energy returned to grid [MW-hr]
S	energy stored [MW-hr]
TCM	maximum generating capacity in turbine mode [MW]
TCm	minimum generating capacity in turbine mode [MW]
TP	total pumping capacity [MW]
ξ	fraction of full turbine capacity
ηo	overall efficiency
$\eta p, \eta t$	pump and turbine efficiency, including electric component.
ηe	penstock efficiency, 0.975.

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