Derivation of Robust Storage Targets for Large Scale Pumped Hydro Energy Storage using PLEXOS

J.P. Deane, E.J. McKeogh, B.P. Ó Gallachóir

***Abstract*—This paper examines the modelling of large scale pumped hydro energy storage in future power systems where variable generation, primarily in the form of wind generation is the dominant source of power generation. It is shown that current deterministic modelling techniques do not give a correct valuation to pumped hydro storage and can in cases overvalue the resource. A methodology is proposed, using stochastic optimisation where historic wind data in conjunction with weekly wind energy forecasts are used to derive weekly and daily targets for storage reservoirs that are adequately robust to manage wind variability and uncertainty. This is ongoing work and as such brief preliminary results are presented in this paper.**

***Index Terms*—Pumped Hydro Energy Storage, Stochastic Optimisation.**

I. INTRODUCTION

Decarbonisation of the power sector is fast becoming a key policy objective underpinning European and Global energy policy and one that is seen to be key in achieving a sustainable future. The means of achieving high levels of decarbonisation are still being debated but what is certain is that the power sector is set to undergo many changes over the next few decades. Within the EU targets related to energy and climate change for the year 2020 are driven by the 20-20-20 initiative [1]. This package of policies aims to reduce greenhouse gas emissions by 20%, to increase the share of renewables in energy use by 20% and to improve energy efficiency by 20%. These and similar policy measures have spurred massive growth in renewable energy across the globe, mainly in the form of wind energy with installed capacities of over 3400 GW predicted by the year 2050 (ref). While wind energy generation is a clean and relatively cheap power source, it is not without its drawbacks, namely in the form of variability and predictability. Power system issues associated with wind energy's variability and predictability are well documented [2] and have been the focus of many wind integration studies which are summarized in the following [3]. The extent to which any power system can accommodate variations in electrical supply is governed to a large degree by its flexibility. Pumped Hydro Energy Storage (PHES) is often cited as a potential technical facilitator for large scale wind energy integration due to its inherent flexibility, quick start characteristics and its ability to store excess energy [4]. A recent working paper by the IEA illustrated the connection between wind power variability and possible required energy storage for the year 2050 [5]. The analysis showed that energy storage capacities of up to 90 GW may be required for very high wind variability scenarios in Western Europe. During the next 8 years, over 7 GW of PHES may be added to the European network [6] with a predicted doubling of PHES capacity within Europe by 2050 [7] indicating a renewed interest in this technology.

While PHES may appear to offer a solution to wind inherent variability it is not a panacea and it is generally accepted that pumped storage, by itself, is an inefficient means of managing variable renewable generation due to its high capital costs and energy and power capacity constraints. Indeed a range of measures exist to increase the flexibility of power systems and facilitate the integration of high levels of variable generation from demand side management to better interconnection. A comprehensive overview of these options is provided in [8]. However PHES may make a contribution towards managing variability as part of a portfolio with interconnection and flexible generation [9]. As wind penetrations levels increase, curtailment, in addition to other power system issues, is likely to become more prominent [10]. PHES can potentially help the integration of renewables by avoiding curtailment [11] and through its inherent flexibility and operating characteristics make a contribution to power system operation.

The concept of using PHES to reduce wind curtailment is relatively simple: in times of excess wind generation PHES can store this excess capacity and release it later when wind output is low. While in theory this concept is simple, in practice it may not be as knowledge of when excess wind generation will occur is uncertain and in order for a PHES to store excess wind generation it must have reservoir capacity to do so. If a storage reservoir is full or almost full then this limits its capacity to pump and store energy, likewise if it is empty or almost empty it limits its capacity to generate. In an operational environment the operator of storage has no

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firm knowledge about future wind outputs. Information is available in the form of wind energy forecasts which have uncertainty associated with them. An operator thus has to make a decision '*here and now'* on the dispatch of PHES that has consequences for the effectiveness of PHES ability to store or generate electricity in the future. If too much capacity within the storage reservoir is spilled 'now' it may compromise the storages ability to generate later. When storage operation is examined in the context of this uncertainty it is shown within this analysis that more conservative release decisions are made in comparison to release decisions that are made under the assumption of perfect foresight.

In this context, the modelling of large PHES in a power system with significant wind penetration is addressed and in particular the challenges associated with the dispatch of large energy storages in an environment with wind forecast uncertainty. The problem is addressed from a Transmission System Operator (TSO) point of view. The TSO is mandated with the safe, secure, reliable, economical and efficient operation of the transmission and power system.

The fundamental question addressed is how to formulate the best dispatch policy for large energy storage (from a system point of view) in the context of high wind penetration without firm knowledge of future wind energy production.

Section II provides a review of current deterministic and stochastic modelling techniques while section III presents the modelling methodology used in this analysis and the test system. Section IV draws conclusions from results.

II. REVIEW OF STOCHASTIC AND DETERMINISTIC MODELLING TECHNIQUES

Deterministic techniques for optimisation of power systems using linear programming/mixed integer programming (MIP) and dynamic programming (DP) have traditionally been the tool of choice for many utilities for deciding unit commitment and economic dispatch in power markets. A good overview of these methodologies is provided in [12]. Stochastic modelling addresses a natural short-coming in deterministic techniques by allowing for the including uncertainty in the modelling process. This is especially important for large storages which may need to be optimised over long periods of time in the context of uncertainty. Uncertainties facing energy companies in liberalized energy markets range from the development of fuel prices for electricity to plant availability. Modelling power systems deterministically with perfect foresight may provide lowest cost solutions for system dispatch but also may provide unrealistic results. If uncertainty is accounted for it is generally accepted that more conservative solutions should be chosen. While Monte Carlo simulations give optimal solutions for a number of scenarios assuming perfect foresight for each scenario it cannot give insight into what decisions should be made now given the uncertainty in the inputs. The goal of stochastic optimisation is, while accepting that uncertain inputs have definable probability distributions, to find a dispatch that is feasible for all possible data instances. Stochastic optimizations mimics real power system dispatches because the decision maker makes a decision based on information at hand, after which a random event occurs and then recourse has to be taken. To cope with different uncertain parameters several stochastic modelling approaches have been developed in the past few years and [13] provides a good overview and classification of these approaches dealing with price risks in electricity markets but does not provide a synopsis of models dealing with fluctuating feed-in of renewable generation. In [14] the authors investigate the cost of wind intermittency in Germany by applying a stochastic electric market model. The results indicate that the value of intermittent resources was generally overestimated applying a static deterministic model. Qualitative differences between deterministic and stochastic approaches in solving the unit commitment problem are discussed in [15] and show that deterministic solutions with perfect foresight will be characterized by extensive use of large plants with high start up costs, with relatively few starts overall. Stochastic solutions on the other hand will typically use smaller units and will involve more start-ups of flexible but possibly high marginal cost plants such as OCGT's. Deterministic models with perfect foresight will know exactly how much power is needed at any time and can plan to run low fuel cost plants at high output for long periods of time. Typically the gains that the model sees for such scheduling will outweigh the high start up cost that come with such plant.

Quantitative differences between deterministic and stochastic solutions for the Irish power system are detailed and presented in [16] using the WILMAR tool. In the study 3 cases were examined. Firstly a case with perfect foresight where realized values of wind and load where the same as expected values. Secondly, a deterministic case which assumed one expected value of wind and load and finally a stochastic case with a range of expected values of wind and load. Lowest system costs were achieved with perfect foresight, with stochastic optimisation producing results approximate 0.8% higher and deterministic optimisation producing result that were approximately 0.9% higher again assuming 3 hour rolling planning. The study also highlighted the importance of accurate modelling of provision for replacement reserves when quantifying the benefits of stochastic optimisation.

A. Storage Modelling

In contrast with thermal generation, whose operation is decoupled in time (except large baseload plant with high startup/shutdown cost), PHES systems are coupled in time that is, a decision today affects operating costs in the future. For example the decision to release or hold water today may inhibit or enhance the ability to capture and store excess generation in the future. Therefore modelling of PHES systems should take into consideration wind power forecasts and thermal unit commitments as these interdependencies are fundamental to actual system operation.

Deterministic modelling techniques with perfect foresight for modelling large PHES may not give a correct valuation to storage and can in cases derive release strategies that are either too liberal or unrealistic. Figure 1 below shows end volume levels for a storage reservoir (1 GW capacity and 50 GWh's of storage) using a daily and monthly optimisation in a test system with high wind penetration and thermal plant. Daily optimisation of large storage is erroneous and cannot be used as the storage attains it bound outside of the simulation horizon. Lengthening the simulation horizon exploits more reservoir capacity, however as perfect foresight is assumed uncertainty is not accounted for. Release strategies are also seen to be overly optimistic insofar as the reservoir reaches its maximum and minimum capacity a number of occasions during the year. From a TSO point of view this would be a bad strategy as it would limit the storages ability to be flexible.

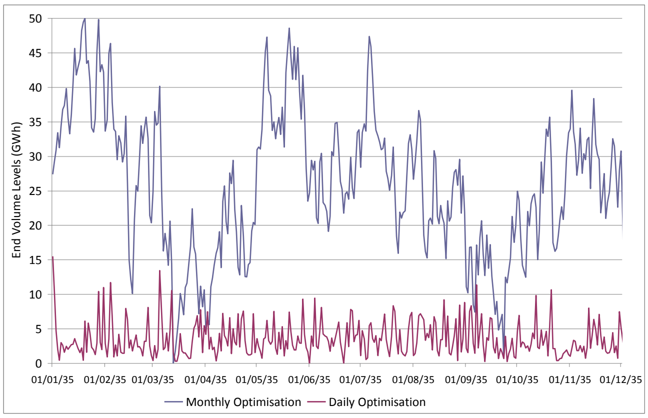

Figure 1: End of Day reservoir levels for both a monthly and daily optimisation of power system. Storage Capacity is 50 GWh and has a rating of 1GW

In summary dispatch schedules produced using perfect foresight, while providing least cost solutions from a system perspective, deviate from reality of the actual system operation as variable generation and load does exactly what is expected. Stochastic methods produce more robust schedules which can respond accordingly to the uncertain nature of power system operation.

III. APPROACH AND METHODOLOGY

Intertemporal constraints such as hydro energy limits are an inherent feature of power system modelling. The methodology presented here specifically deals with closed-loop PHES (i.e. no hydro inflow) in power systems with high wind penetration. In this context PHES is primarily used to manage wind variability and intermittency. In this approach the software PLEXOS is used to solve medium and short-term PHES constraints in two-stages. In the first stage, *ST schedule* is used to stochastically optimize weekly targets for PHES over the course of a year using long term historic wind data as a stochastic variable. In the second stage, *ST Schedule* is again used stochastically to derive end of day targets for storage for each day of the week while also enforcing weekly targets derived in step one. The software has the capability to decompose medium term to long-term hydro energy limits however PHES is optimized by ST independently of MT. A detailed methodology is provided in Section C below. Firstly the test system in presented in section A and the modelling software is detailed in section B.

A. Test system

The test system modelled is the All-Island (AI) and Great Britain (GB) market in 2035. The year 2035 was chosen as a test year and it is assumed that high levels of variable renewables will be present in both systems. The test system presented, while satisfying security of supply standards, is not intended to be an optimal portfolio, and is merely used as a test bench for modelling techniques. The All-Island system is connected to GB with 2000 MW of interconnection. The potential benefits of interconnection for the Irish system from a wind energy integration point of view are well documented [17]-[18] . Electricity demand for the island of Ireland in 2035 is assumed to be approximately 47 TWh with a peak of 7.8 GW. Electricity demand for the GB system in 2035 is assumed to be 398 TWh with a peak of 106 GW. Generation units and unit capacity used for each region are detailed in Table I while fuel price assumptions are presented in Table II. The AI system has one 1 GW PHES units with 50 GWh of storage. One year of hourly wind farm capacity factors (in time series format) for 4 regions in Ireland from 2008 were scaled up to match 2035 wind capacity values. Wind farm capacity factors in GB are lagged by a number of hours to give correlations between the AI wind and GB wind outputs as published in [19]. This type of approach to the development of wind profiles in GB is not ideal and further work is required on this matter. Tidal stream data for the year 2035 was used to develop power output for a tidal energy device similar to [20]. Wave height and period data off the west coast of Ireland for the year 2008 was used to develop power output for the *Pelamis* wave device [21]. The year 2008 was chosen so as to correlate with concurrent wind data. This analysis does not consider detailed modelling of transmission issues, frequency and inertia issues of voltage stability. Recent studies by EirGrid estimate that instantaneous power from wind and imports may have to be limited to 70-80% of demand within the AI system due to these issues [22]. In this analysis wind penetration levels in the AI system are limited to 80%.

Table I
Portfolio Characteristics

Type of Generation	Capacity (GW) AI	Capacity (GW) GB	Emissions in kgCO2/MWh
Wind	8.5	28.1	0
Other renewables	1.7	21.8	0
CCGT	1.4	36.1	340
OCGT	2.3	2.0	580
Interconnector	2.0	5.0	0
Pumped Storage	2.0	1.8	0
Nuclear	0	8.0	0
CCS Coal	0	8.8	40

Non-CCS Coal/Oil	0	1.7	710
Total	21.9	113.3	

Table II
Assumed fuel and carbon prices

Fuel	2035 AI Price	2035 GB Price
Gas	10.59 €/GJ	10.39 €/GJ
Coal	-	2.80 €/GJ
Carbon	€60/tonne	€60/tonne

B. PLEXOS Model

The modelling software used in this analysis is *PLEXOS for Power Systems* developed by Energy Exemplar [23]. In this analysis PLEXOS is run both deterministically and stochastically. The stochastic configuration uses 2 stage stochastic mixed integer programming (MIP) to determine least cost unit commitment and dispatch solution. The model is configured to undertake a year of optimizations with specified look ahead periods at varying resolutions. The simulation proceeds by solving these steps in chronological sequence. The model solves using the Xpress MP solver [24] with optimality gap set to 0.1%. The model is populated with individual generator technical characteristics such as maximum and minimum generation levels, maximum ramp rates (up and down), start costs, heat rates, variable operation and maintenance costs, mean time to failure, mean time to repair. Stochastic settings force non-anticipativity on manually selected inflexible units and in this analysis PHES. Non-anticipativity ensures that the first stage stochastic variables (unit commitment decisions) are identical across second stage decision scenarios (dispatch). The first stage decisions represent *here-and-now*-decisions which are applied regardless of the future evolution and thus have to be identical for all scenarios. Second stage decisions are scenario-dependent recourses. The classic two stage stochastic linear problem with recourse is described in [25].

C. Proposed Methodology

A two step methodology is proposed which aims to derive robust weekly and daily storage targets for large PHES from a system operator point of view. The storage targets derived in this methodology are 'robust' in the sense that they schedule PHES dispatch in such a fashion that the end of day reservoir targets for one day are sufficiently adequate to cope with uncertainty and variability in wind energy in the coming days and weeks. In other words, the methodology gives the operator insight into what decision to make today so as not to compromise PHES's ability to manage system and wind variability in the future. The model also considers forced and unforced outages for all thermal plant. Figure 2 provides a schematic overview of the proposed approach.

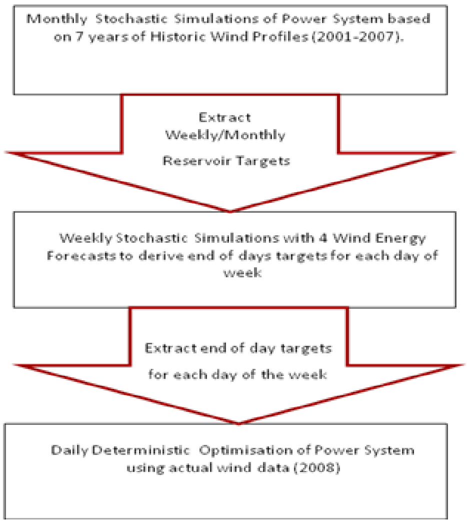

Figure 2: Schematic of two stage approach to development of robust targets for PHES in high wind systems

The first step of the methodology is the derivation of weekly and monthly targets. In a wind dominated power system it is assumed that PHES is acting to manage or 'counter' wind variability and unpredictability. In this context long term historic wind data is used to derive the appropriate weekly and monthly targets for storage levels. Seven years of actual 15 minute wind profiles were obtained for a number of regions in the All Island system. These were inputted into PLEXOS as **.csv* files, with one file per region (4 regions) and each file containing 7 years (7-bands) of data. A monthly stochastic optimisation of the complete system with an 8 hr time resolution and 1 month 'look-ahead' was undertaken across all historic years of wind data in the ST-Schedule. These setting were chosen so as to ensure the large storage attained it bounds within the simulation horizon and also to make the program files manageable for the computer system. Stochastic setting for storage force trajectory non-anticipativity. This means storage trajectory decisions are identical across all samples of historic wind data thus produces one release policy that is robust for all given scenarios of wind. This is in comparison to running an *Independent Samples* analysis which runs one deterministic optimisation for each individual year of wind data with the same simulation horizon and interval step. Figure 3 below shows the End volume levels for the storage reservoir over the course of a year. A deterministic optimisation was carried out for each individual sample year of wind data. These results are show in grey. It can be seen that some years the reservoir releases are overly optimistic with the reservoir reaching maximum and minimum capacity a number of times. The average of these samples which is shown in black gives more appropriate release decisions for storage however this is the average of individual simulations whereas the stochastically optimized storage levels shown in red are optimized in one simulation across all presented 7 scenarios of wind and is optimal considering all these. This leads a more robust storage target development as the complete system and storage can manage a large range of possible wind variations.

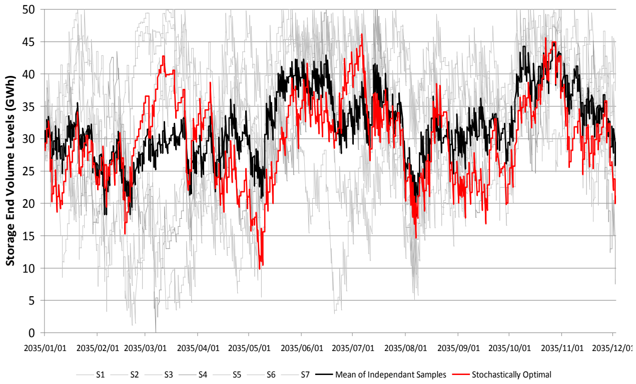

Figure 3: Daily End volume levels for storage reservoir over a year for 7 deterministically optimized sample years of wind data in grey. Average of optimizations is shown in black. Red line is stochastically optimized end volume levels over the same 7 sample years of wind data.

The end of week storage levels for the upper reservoir in GWh were extracted and written out to text file and used in Step two of the process.

Step two of the process aims to form a bridge between the derived weekly storage targets and daily storage targets. Daily storage targets should be set so as to give PHES adequate flexibility to deal with daily variability in the power systems but also ensure that PHES finishes each day with capacity and in a position to manage the next day's and number of days variability and unpredictability of wind.

Daily storage targets for each day of the week are developed using a weekly wind energy forecast. In this analysis four 7 day wind energy forecasts are synthesized within the variable class of PLEXOS by an endogenous sampling method which draws random samples around an expected value. In total 52 forecasts are used, one for each week. The expected values are hourly wind profiles for the 4 corresponding regions on the All Island system for the year 2008. Within the PLEXOS software a Brownian motion with mean reversion model is used to develop samples around the expected value assuming an error standard deviation of 12%. In practice actual wind forecasts can be used, however due to time constraints synthesized values were used here. The power system was again stochastically optimised forcing storage decisions to be the same across the full range of forecast scenarios. A weekly optimisation with a two hour time step was used with end of week targets from step 1 enforced as hard constraints. A weekly optimisation was employed because it is necessary to bridge daily and weekly targets. End of day targets were extracted and written to a text file.

To test the method and robustness of derived targets the power system was run deterministically on a daily basic with actual wind data from 2008. This data was chosen so as to mimic the reality that TSO's don't have firm knowledge of wind speeds in advance. Storage targets so far were determined using either long term historic data or forecast data but not actual realized wind data. Within the model run, daily and weekly storage targets were enforced as hard constraints however the storage was free to manoeuvre within the day as required to deal with variability.

At the time of writing only preliminary results were available. Full result regarding systems cost and reliability of the system will be published at a later date. The table below presents a brief comparison of total systems costs for the power system operated in a deterministic fashion with perfect foresight and operated with this proposed methodology to derive daily and weekly storage targets.

Table III: Relative comparison of system costs for power system optimized with deterministic optimisation and proposed methodology.

	Proposed Methodology
Relative increase in System Cost compared to deterministic optimisation of system with perfect foresight	+0.27% (Total System)

It can be seen that when this methodology is employed system costs rise marginally in comparison to dispatches that are undertaken with perfect foresight. However it must be borne in mind that the systems optimised under this methodology is more robust and storage is in a stronger position to manage wind unpredictability and variability.

IV. CONCLUSION

This paper presented a methodology to derive robust storage targets for PHES in powers systems with high wind penetration using stochastic optimisation of historic and forecasted weekly wind profiles. The methodology was applied in a power system with 1 year of daily optimisations. The methodology was seen to provide robust targets for storage operation in the context of wind variability and intermittency.

The presented work is part of ongoing work investigating the modelling of storage in high wind systems and is thus a work in progress. Future work will aim to improve on the proposed methodology and aim to quantify and quality potential benefits for wind energy integration from a TSO viewpoint. It is thought that the inclusion of storage targets as 'slack constraints' rather than 'hard constraints' may improve the modelling process. This is currently being tested.

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