Production of Hydrogen from Wind and Hydro Power in Constrained Transmission grids, Considering the Stochasticity of Wind Power

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Production of Hydrogen from Wind and Hydro Power in Constrained Transmission grids, Considering the Stochasticity of Wind Power

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Abstract. Producing hydrogen from renewable energy sources can be used as a way of extracting large quantities of energy from remote regions far from load centers. These regions have weak transmission grids and building new transmission lines are expensive due to large distances. The tight restrictions on the power systems in these regions makes daily operation difficult and unexpected variations in wind power production can have significant negative impacts, such as rationing of power.

A stochastic rolling horizon model is formulated and implemented to consider the importance of including wind power stochasticity when operating flexible hydrogen loads in a congested power system. Wind power scenarios are created using realized wind power production and meteorological weather forecasts. The resulting operation plans of hydrogen storage and hydro power plants, using expected values or wind power scenarios, are tested and compared in a simulator with the realized wind power production.

Results from the case study show that the stochastic model gives a better strategy than the deterministic model which use the expected value of wind production by about 5.6% and there is potential for further cost reductions by improving the forecasting. When including more than 27 wind power scenarios the changes in results are small. The case study also shows that hydrogen storage is important to avoid rationing in certain situations and increase power flow.

1. Introduction

The best wind resources both on- and off-shore are often located in remote areas far from load centers. New transmission lines have to be constructed in order to exploit these excellent resources and export the energy over large distances. This requires large investments which must be considered when calculating the socioeconomic benefit of these wind power projects and often makes them unprofitable[1]. In Norway, this is the case for the northern pars of the county, where there are exceptionally good conditions for wind power production. A wind turbine in this region can produce up to twice as much energy as a wind turbine in southern Norway, comparable with offshore wind turbines but at significantly lower costs. The grid connection between northern and southern Norway, where most of the people and consumption is located, is too weak to support integration of large amounts of wind power in the north [2]. Producing hydrogen and exporting liquefied hydrogen (LH_2) on ships, similar to liquefied natural gas (LNG) can be a good option for utilizing the wind resource.

Nomenclature

Indices

i, j	Bus
s	Second stage node
t	Time stage

Parameters

Δ	Price addition for import [€/MW]
$\eta^{d/s}$	Conversion factor from power to hydrogen [MWh/Nm^3], directly from electrolyser or from hydrogen storage
λ_t^s	Spot price [€/MWh]
ρ_s	Probability of wind power scenario
C_t^d	Cost for changing production from plan [€/MWh]
$C^{r/i}$	Cost of rationing [€/MWh] or hydrogen import [€/Nm^3]
$C^{v+/v-}$	Cost for violating end reservoir level [€/MWh]
D_{ti}	Electricity demand [MWh]
E_i^{max}	Capacity of electrolyser [MW]
H_t^D	Hydrogen demand from electrolysis [MWh]
H_i^{max}	Capacity of hydrogen storage[Nm^3]
I_{ti}	Inflow to hydro power reservoirs [MWh]
$P_{ti}^{min/max}$	Min or max power production [MW]
P_{tis}^w	Wind power production scenario [MWh]
S^{ref}	Reference power for the system [MW]
T_{ij}^{max}	Transmission capacity from bus i to j [MW]
$V_i^{0/max}$	Initial volume or max capacity for reservoir [MWh]
X_{ij}	Reactance on line between bus i and j [$p.u.$]

Sets

$\mathcal{B}$	All buses
$\mathcal{C}_i$	Buses connected to bus i by transmission lines
$\mathcal{H}, \mathcal{W}, \mathcal{P}, \mathcal{H}_2$	Hydro power, wind power, all power plants or hydrogen plants
$\mathcal{N}$	All normal buses (Market bus excluded)
$\mathcal{S}$	Wind Power Scenario
$\mathcal{T}$	Time stages

Variables

δ_{tis}	Voltage phase angle at bus
c_{tis}	Energy curtailment [MW]
$d_{tis}^{H_2-/+}$	Negative/ positive change in hydrogen production [MW]
$d_{tis}^{hydro-/+}$	Negative/ positive change in hydro power production [MW]
f_{tijs}	Power flow from bus i to j [$p.u.$]
h_{tin}^d	Hydrogen supplied to load directly from electrolyser [Nm^3]
h_{tis}^{imp}	Hydrogen imported/ not served [Nm^3]
h_{tin}^p	Hydrogen production from electrolysis to storage [Nm^3]
h_{tin}^s	Hydrogen supplied to load from storage tanks [Nm^3]
h_{tin}	Level of hydrogen in storage tank [Nm^3]
$p_{tis}^{imp/exp}$	Power import or export [MW]
p_{tis}	Production [MW]
r_{tis}	Rationing of power [MW]
s_{tin}	Spillage/ bypass of water [MWh]
$v_n^{+/-}$	Violation of end reservoir level [MWh]
v_{tin}	Reservoir level [MWh]

A project headed by SINTEF Energy Research called HYPER looks at the possibility of producing hydrogen, both from natural gas with carbon capture and storage (CCS) and from hydro and wind power. The locations of natural gas resources are often co-located with good wind resources, both on-shore and off-shore. In the case of northern Norway there are already production of LNG from natural gas.

Several positive effects can be obtained by producing LH_2 instead of LNG and storing the CO_2 in depleted natural gas reservoirs. Firstly, emissions from the use of natural gas as a energy source is greatly reduced by storing the CO_2 at the production site where there are storage capacity in the depleted natural gas reservoirs. Secondly, this creates infrastructure for liquefaction of hydrogen and a supply chain to the to the energy demand, this can be used

to accelerate the development of wind power by producing hydrogen through electrolysis. The costs of electrolysis plants are dropping and are competitive for large plants, the most critical cost element when considering the profitability of such a plant is in fact the cost of energy which in this case is very low. Thirdly, producing hydrogen from wind power in a flexible manner by including hydrogen storage can increase the utilization of existing transmission lines and reduce the amount of new transmission capacity needed to develop wind power. Utilization of transmission lines in regions with large amounts of wind power is low due to the variable nature of wind power and the correlation between wind farms. Closely located wind farms are often producing or idle at the same time creating congestion at one time and no line utilization at another time. This correlation problem is reduced the grater the area that is considered due to the smoothing effect, but can still have a significant impact.

Wind-hydrogen systems is extensively studied in the literature. In [3] a local wind-hydrogen system is studied where they consider wind power by using deterministic forecasts to make a plan for trading power in the spot-market and then simulates imbalances settled in the balancing market using a receding horizon approach. The system consist of one bus with wind generation, electrolyser, hydrogen storage, fuel cell, electrical load, hydrogen load and a connection to the external grid. The case study showed that the fuel cell was only used for cases with large energy price variations and high imbalance costs.

Hydrogen production in weak transmission grids are studied in [4] and [5]. In [4] they use a logistic simulation model to study the effects on wind power integration and sizing of hydrogen storage by including hydrogen loads. While in [5] they use a optimization model and also include fuel cells. The results show there is large benefits using a grid connected setup in terms of electrolyser sizing and operating conditions.

The authors have previously presented a method for optimal sizing of components for large scale hydrogen production in a regional power system with congested transmission lines, wind and hydro power [6]. The results show that the sizing of the hydrogen storage and integration of wind power is highly dependent on the grid configuration, hydrogen storage is very important to avoid rationing if the region is weakly connected to the rest of the system.

Rolling horizon models frequently used when studying integration of wind power in the power system. In [7] they use a stochastic rolling horizon model with wind power scenarios for a system consisting of a wind farm and batteries to study the effects of considering battery degradation when bidding in the real-time electricity market. In a system level study in [8] they use a rolling horizon model to study the effects of large scale wind power integration in Ireland. The model includes a detailed description the power system with unit commitment constraints and representations of the spot and reserves markets. They update the plans every 3 hours and the results show that 34 % of the load inn the Irish power system can be provided by wind power.

The model presented in this paper is a rolling horizon model for studying the storage strategies of flexible hydrogen production and hydro power. The model includes stochastic wind power and is different from the [8] as it includes storage and a linearized representation of the transmission grid, but not unit commitment constraints. The model use scenarios of wind power production such as in [7] with equal probability and find the storage strategy that is best considering all scenarios.

The rest of the paper is organized as follows, in Chapter 2 the three most important parts of the model is presented; the generation of wind power scenarios, the planning model and the simulator model. A case study based on the region of northern Norway is outlined in Chapter 3. The results from the case study are presented in Chapter 4 and the conclusions are given in Chapter 5.
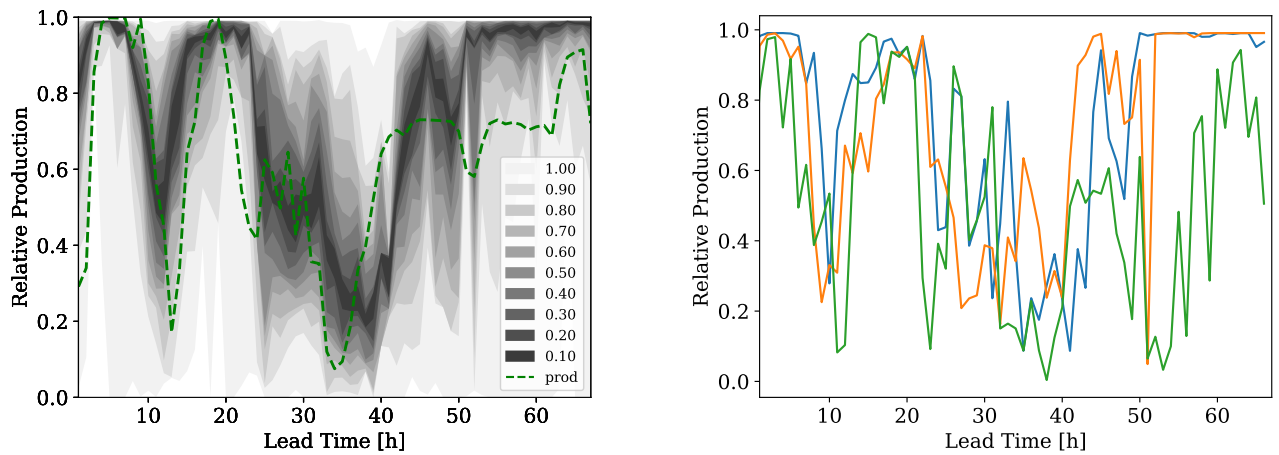
(a) Quantile forecast of relative production for Rag-govidda wind farm in northern Norway.

(b) Scenarios of wind power production sampled from the quantile distribution.

Figure 1: Quantile forecats are used to creating wind power scenarios for the stochastic model.

2. Model

The model presented in this paper is a model for a regional power system with flexible hydrogen loads, wind and hydro power. The model consist of three main parts, wind forecasting, strategy calculation and simulation, these parts are explained in detail in this chapter.

2.1. Wind Power Scenarios

The representation of wind power uncertainty is obtained by sampling production scenarios from quantile forecasts as explained in detail in [9]. In short the method consist of random sampling from a multivariate normal distribution using a correlation matrix representing temporal and spatial correlations. The sampled values are matched by their probability in the cumulative distribution function (cdf) of the normal distribution, the wind power production scenario is obtained by matching these probabilities in the cdf of the quantile distribution.

The quantile forecasts are created by using histrorical metrological forecasts from The Norwegian Meteorological Institute and production records from existing wind farms obtained from The Norwegian Water Resources and Energy Directorate. The data is used in a local quantile regression algorithm for generating the quantile forecasts as in [10], a example of an quantile forecast for the wind farm Raggovidda is shown in Figure 1a.

2.2. Planning Model

The planning model optimize the expected cost of operating a region of the power system, all the electrical and hydrogen demand has to be served either by using generation from within the region or by importing power from the external power market. This can be modelled as optimizing profit from selling power to the external market as stated in the first two terms in the objective function in Equation (1). Power is sold to the market node at the spot price or it can be purchased from the market node for the spot price plus tariffs. Penalty terms are added in each time step for rationing of power, import of hydrogen from external sources, deviation from scheduled power consumption for producing hydrogen and deviation from production plans for hydro power. Predefined reservoir handling curves are used to represent the long term hydro power strategy, deviation from these plans at the end of the planning horizon are penalized in the final term of the objective function.

$$\max \sum_{s \in \mathcal{S}} \rho_s \Bigg[\sum_{t \in \mathcal{T}} \Big[\lambda_t^s p_{t0s}^{imp} - (\lambda_t^s + \Delta) p_{t0s}^{exp} - \sum_{i \in \mathcal{N}} C^r r_{tis} - \sum_{i \in \mathcal{H}_2} C^i h_{tis}^i - \sum_{i \in \mathcal{H}_\in} C_t^d (d_{tis}^{H_2-} + d_{tis}^{H_2+})$$

$$- \sum_{i \in \mathcal{H}} C_t^d (d_{tis}^{hydro-} + d_{tis}^{hydro+}) \Big] - \sum_{i \in \mathcal{H}} (C^{v+} v_{is}^+ + C^{v-} v_{is}^-) \Bigg] \qquad (1)$$

s.t.

$$p_{tis} + c_{tis} = P_{tis}^w \qquad\qquad \forall i \in \mathcal{W}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (2)$$

$$v_{tis} = v_{(t-1)is} - p_{tis} - s_{tis} + I_{ti} \qquad\qquad \forall i \in \mathcal{H}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (3)$$

$$v_{0is} = V_i^0 \qquad\qquad \forall i \in \mathcal{H}, \forall s \in \mathcal{S} \qquad (4)$$

$$v_{Tis} - v_{is}^+ + v_{is}^- = V_{T,i}^{curve} \qquad\qquad \forall i \in \mathcal{H}, \forall s \in \mathcal{S} \qquad (5)$$

$$h_{tis} = h_{(t-1)is} + h_{tis}^p - h_{tis}^s \qquad\qquad \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (6)$$

$$h_{tis}^d + h_{tis}^s + h_{tis}^i = H_{tis}^D \qquad\qquad \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (7)$$

$$\sum_{j \in \mathcal{P}_i} p_{tjs} - \eta^d h_{tis}^d - \eta^s h_{tis}^p - p_{tis}^{exp} + p_{tis}^{imp} + r_{tis} = D_{ti} \qquad \forall i \in \mathcal{N}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (8)$$

$$d_{tis}^{H_2-} - d_{tis}^{H_2+} = \eta^d (h_{ti}^{d,plan} - h_{tis}^d) + \eta^s (h_{ti}^{p,plan} - h_{tis}^p) \qquad \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (9)$$

$$d_{tis}^{hydro-} - d_{tis}^{hydro+} = (p_{ti}^{plan} - p_{tis}) \qquad\qquad \forall i \in \mathcal{H}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (10)$$

$$p_{ti}^{exp} - p_{ti}^{imp} = S^{ref} \sum_{j \in \mathcal{C}_i} f_{tij} \qquad\qquad \forall i \in \mathcal{B}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (11)$$

$$f_{tijs} = \frac{1}{X_{ij}} (\delta_{tis} - \delta_{tjs}) \qquad\qquad \forall j \in \mathcal{C}_i, \forall t \in \mathcal{T}, \forall i \in \mathcal{B},$$

$$\forall s \in \mathcal{S} \qquad (12)$$

$$0 \leq v_{tis} \leq V_i^{max} \qquad\qquad \forall i \in \mathcal{H}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (13)$$

$$P_{ti}^{min} \leq p_{tis} \leq P_i^{max} \qquad\qquad \forall i \in \mathcal{H}, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (14)$$

$$0 \leq \eta^d h_{tis}^d + \eta^s h_{tis}^p \leq E_i^{max} \qquad\qquad \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (15)$$

$$0 \leq h_{tis} \leq H_i^{max} \qquad\qquad \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T}, \forall s \in \mathcal{S} \qquad (16)$$

$$- T_{ij}^{max} \leq f_{tijs} S^{ref} \leq T_{ij}^{max} \qquad\qquad \forall j \in \mathcal{C}_i, \forall i \in \mathcal{B}, \forall t \in \mathcal{T},$$

$$\forall s \in \mathcal{S} \qquad (17)$$

Potential wind power production has to be used for wind power production or it has to be curtailed as stated in Equation (2), potential wind power is the only time series which is dependent on scenario as shown by the subscript s. Hydro power reservoirs are governed by the reservoir balance in Equation (3), initial reservoir level is stated in Equation (4) and end reservoir has to follow the handling curve in Equation (5). The storage balance for hydrogen is governed by Equation (6), while the hydrogen balance in Equation (7) states that hydrogen demand can be supplied either by hydrogen directly from the electrolyser, from the storage tanks or from imported hydrogen from other sources.

The energy balance in Equation (8) states that production from wind and hydro power and exchange has to supply consumption by the hydrogen production plant and normal electricity demand. Rationing can be used as an option to balance the production and demand but to a significant cost. A common plan for hydro power production and hydrogen plant power
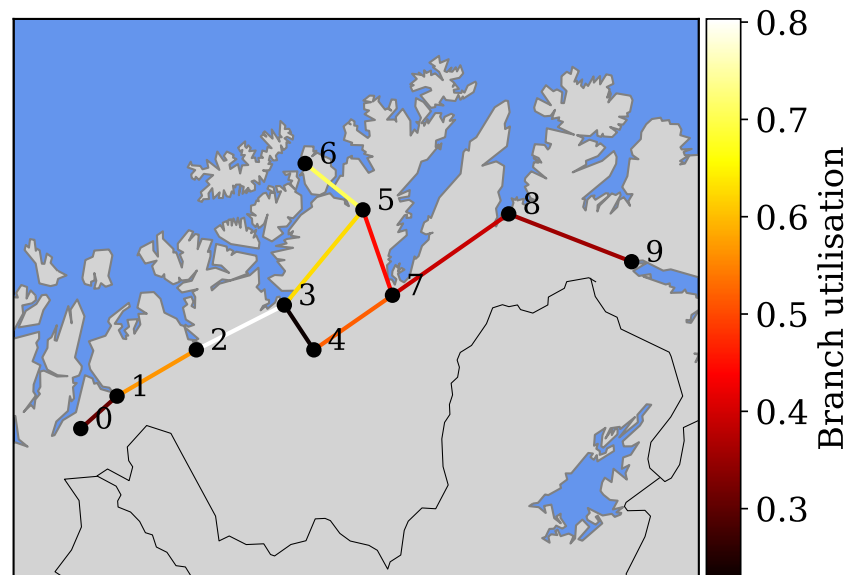
Figure 2: Case study system based on the power system in Finnmark, northern Norway. Lines are colored according to the line utilization in the run with 120 wind power samples. Power is on average flowing from both ends towards node 6.

consumption for all scenarios is the main output from the planning model, the production in each scenario can deviate from these plans as shown in the deviation constraints in Equation (9) and (10), but deviations are penalized in the objective function. This penalization of deviations are necessary as hydro power is modelled by aggregating plants to one plant per bus, if more detailed modelling of hydro power such as start-up cost, ramping constraint, minimum run time, water travel time was included this penalty would have been represented internally by the model.

The nodal balance for power flow is stated in Equation (11), while the line flow is governed by the dc power flow Equation in (12). Finally limits on reservoir volume, production, electrolyser capacity, hydrogen storage capacity and power flow is represented by Equation (13) to (17).

2.3. Simulator
A simulator is used to test the value of the different strategies, the simulator is based on the same formulation as above but for one single scenario. The single wind scenario used in the simulator is the historical realized production and the plan variables are now input parameters. The simulator use the same scheduling horizon as the strategy model, but only the first 24 hours of the simulator results are used as final results. The storage and reservoir levels obtained in the 24th hour of the simulator is sent back to the strategy model for the next iteration of the planning.

3. Case Study
The case study is based on the region of Finnmark in northern Norway, the region has the best wind power potential in Norway and a facility production of LNG at Melkøya. In [6] the same area is studied and different options for grid expansion and wind power development are

Table 1: Bus data for the case system.

Bus Nr.	1	2	3	4	5	6	7	8	9	Sum
Wind [MW]	10.0	0.0	0.0	0.0	200.5	0.0	0.0	40.0	287.1	537.6
Hydro [MW]	80	85	17.7	145.2	4.2	1.1	1.7	55.1	78.3	468.3
Reservoir [GWh]	224.8	231.9	46.5	56.7	5.0	0.0	1.6	168.5	16.1	751.1
Load [GWh/yr]	225.5	35.1	374.3	22.7	121.5	188.2	136.6	80.2	680.3	1864.4

Table 2: Line capacities for the case system.

Line	0, 1	1, 2	2, 3	3, 4	3, 5	4, 7	5, 6	5, 7	7, 8	8, 9
Capacity [MW]	205	179.5	216.5	109.8	216.5	109.8	426.6	261.8	219.6	205.9

analyzed in light of large scale hydrogen production. The system is shown in Figure 2 and consist of a market bus (0) and 9 normal buses (1-9). The most important bus and line data is shown in Table 1 and 2. The hydrogen plant can serve the hydrogen load directly or via storage, the two conversion factors are estimated to 4.66 kWh/Nm^3 and 4.79 kWh/Nm^3 respectively. The hydrogen production plant is located in node 6 and has a electrolyser capacity of 108 MW and a storage capacity of 101 551 Nm^3.

The price in the regulating power market is representative of the flexibility cost of the system, it follow the power price but are about 10% higher for up regulation which is low compared to other systems. Using such a low price results in little difference when considering the uncertainty of wind power as it costs little to change production plans in real time. As the amount of wind power increase and the region is isolated due to grid congestions this regulating price is likely to increase. In the case study the penalty value for deviation for hydrogen production and hydro power plans is set to the same the power price, thus regulating in real time is twice as costly as making the best plan a day ahead.

4. Results
The rolling horizon model is tested with different numbers of wind power scenarios from one, using the expected wind power production, up to 120 scenarios. The preformance of the model is shown in Figure 3. Figure 3a shows the cost of the regional power system, the cost consist of power exchange cost and flexibility penalties. The red line represent the costs obtained when using the expected wind power for planning the operation as in a deterministic model, this typically results in strategies that are close to the limits of the system and perform badly when tested in the simulator for the realized values. The blue line represents the cost when using different amounts of wind power samples, as the number of samples increases the costs decreases due to a better representation of the uncertainty from wind power. The lowest cost that can be obtained is shown by the green line, in this case the realized wind power production is known in the strategy calculation and no changes needs to be made from the original plan resulting in no penalty costs.

The best solution for the stochastic cases are obtained when 90 samples are used. The value of the stochastic solution (VSS), defined as the difference between the expected value solution and the stochastic solution, is in this case 26 893 € or 5.6 % savings in total costs. The expected value of perfect information (EVPI) is the difference between the stochastic solution and the perfect information solution, which is 180 246 € or 37.6 % of cost reduction from the stochastic solution. Better wind power forecasts can reduce the costs for the stochastic solution
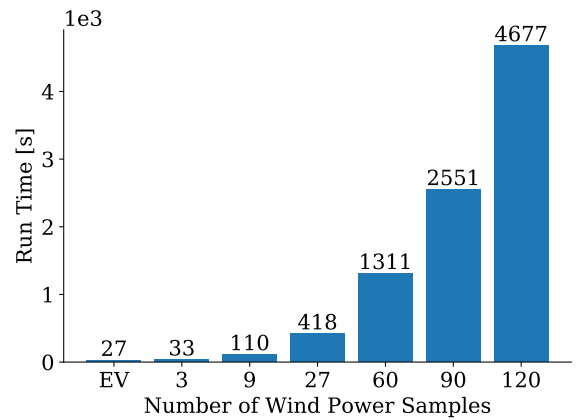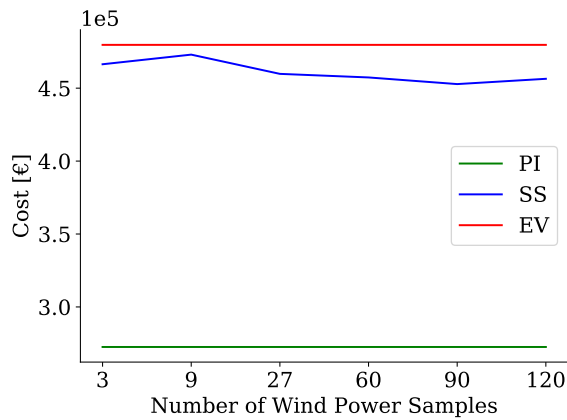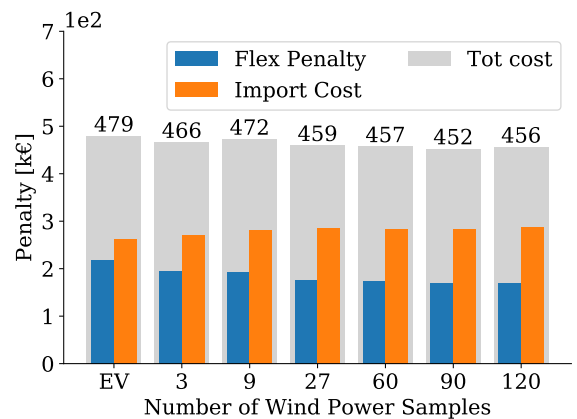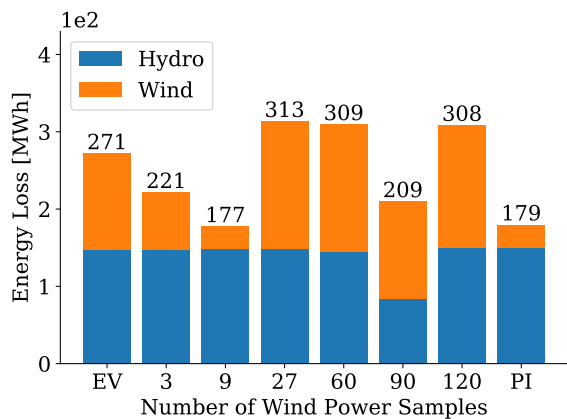
(a) Cost of operating the regional power system using perfect information (PI), stochastic scenarios (SS) or the expected value (EV) in the strategy calculations.

(b) Run time of the strategy calculation, the run time in the simulator is negligible.

Figure 3: Value of the solution and run time for the strategy calculation, showing the performance of the model.

(a) Energy lost from spilling water in hydro power plants or curtailing wind power production.

(b) Breakdown of the total costs obtained in the different runs into penalty and import costs.

Figure 4: Energy lost and cost breakdown.

by capturing some of the saving potential from better information, thus increasing the VSS. Both the VSS and EVPI is dependent on the cost of flexibility, reducing the cost of flexibility reduces these values.

Figure 3b show the time used by the strategy calculations for the different number of wind samples. The solution time increases with the number of wind power samples, there is little gain in cost reduction by having more than 27 samples while the solution time increases significantly.

Figure 4a shows the lost energy due to spillage of water or curtailment of wind, the cases with low numbers of wind scenarios have lower wind curtailment compared to the cases where wind power uncertainty is better represented. However, the cases with high wind power curtailment have more reduction in penalty costs than the increase in import costs which results in lower
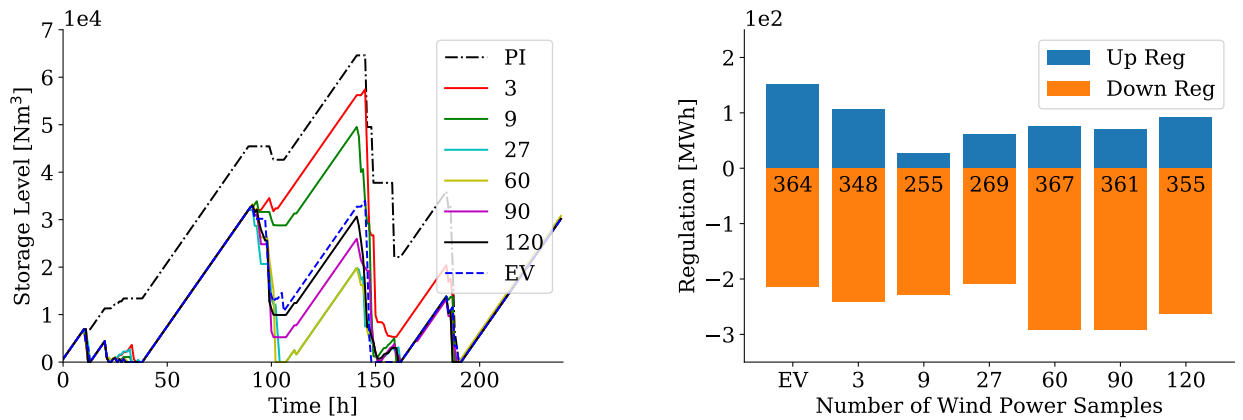
(a) Storage level for hydrogen storage in bus 6.

(b) Up and down regulation of the hydrogen load for the different cases. The total up and down regulation is stated inside the bars.

Figure 5: Hydrogen storage level and regulation of the hydrogen plant.

Table 3: Increased flow on lines as a result of hydrogen storage.

Line	0, 1	1, 2	2, 3	3, 4	3, 5	4, 7	5, 6	5, 7	7, 8	8, 9	Mean
EV [%]	-0.32	0.59	0.70	-1.42	1.03	2.22	0.22	-0.60	-0.77	2.12	0.38
120 [%]	1.22	0.83	0.66	1.36	0.65	0.89	0.22	-0.22	-0.05	1.48	0.70
PI [%]	1.43	0.83	0.67	3.16	0.35	-0.17	0.22	0.13	2.60	2.87	1.21

total costs as seen from Figure 4b. Better utilization of the heavily congested line between node 2 and 3 by more accurate scheduling results in higher imports and lower penalty costs.

The storage strategies for solutions with more than 27 samples are quite similar as seen from Figure 5a, in this case the strategy are approaching the expected value strategy as the number of wind power scenarios increase. These strategies are quite different from the perfect information strategy, the low sample strategies 3 and 9 are actually closer. Figure 5b shows how the hydrogen plant energy consumption is regulated from the planned production, it seems like the there isn't any direct relationship between the amount of wind power scenarios and total regulation but the amount of regulation for 60 to 120 scenarios is very similar and is more down regulated than the rest.

The model is also used on the same case study but without hydrogen storage to test the importance of hydrogen storage and how this changes with wind power scenarios. Table 3 shows the increased power flow on the lines when hydrogen storage is included compared to when it is not, the power flow on the lines is on average increased with 0.38 % when using the expected value, 0.7 % when using 120 wind power samples and 1.21 % when using perfect information. These values are small as the system has a lot of flexible hydro power that can be used instead and might be increased by moving the hydrogen production to another node or distributing it over more buses. The most important difference without hydrogen storage is that it results in rationing in hour 100 due to grid congestion on line (2,3) and (4,7), with storage the hydrogen load can be reduced and rationing avoided.

5. Conclusion

A rolling horizon model was developed for assessing the value of including stochastic wind power in a regional power system with hydrogen production. The case study shows that the stochastic model gives solutions that reduce the costs in the system by 5.6 % compared to a deterministic model based on expected values. Using perfect information gives a solution with 37.6 % reduced costs, these results are dependent on the flexibility cost which is set high in this case. This is also the upper limit for how low the costs can become in the stochastic solution, some of these cost reductions can be gained by improving forecasts etc.

Increasing number of scenarios give better solutions, however increasing the number of scenarios to more than 27 gives little reductions in cost compared to the increased run time. Including hydrogen storage gives increased power flow. The increased power flow due to hydrogen storage could be larger in a less flexible system or if the hydrogen load is distributed over several buses. The most important effect of the hydrogen storage is that it helps avoid rationing in specific situations when the transmission grid is constrained.

6. Future Work

In future work the simulator will be integrated into the strategy model such that the first stage simulate the result with the realized wind and the current plan while the second stage makes the plan for the next day. This would result in the model operating more like the markets work in reality, and is similar to the model sequence in [7]. Additionally a feature where deviations in a small range around the reservoir curve is priced based on the water value instead of the deviation penalty will also be considered.

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