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Coordination of Hydro and Wind Power in a Transmission Constrained Area using SDDP

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Title: Coordination of Hydro and Wind Power in a Transmission Constrained Area using SDDP

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Problem description:

Study how increased wind power in a grid-constrained area affects optimal hydro power production. A simplified model for the power system in Sogn og Fjordane should be created for this purpose. The following sub-tasks are planned:

- Update the SDDP-model to consider power export and other necessary model features.
- Establish data series for inflow, energy prices, local consumption and wind power.
- Establish scenarios for future wind power production.
- Perform analysis of total energy sales, export and flood due to the installed wind power for the hydro power production strategy with or without respect to wind power.

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Abstract

As a part of the initiative to reduce the effects of climate change by moving towards increased shares of energy from renewable sources Norway and many other European countries has stated clear targets described in the Energy Directive. In Norway the main mechanism to achieve this goal is at present the green-certificate market which is a common effort by Norway and Sweden to increase the amount of electricity production from renewable energy sources. Both Norway and Sweden has good conditions for renewable energy production from hydro and wind power, but these resources are often in rural areas where the transmission grid is weak. The weak grid represents an additional cost to implementing renewable energy sources as it requires significant investments in construction of new transmission lines. By controlling the storable hydro power in the region with respect to wind power production and thus utilize the transmission lines more efficiently the required investments in transmission capacity can be reduced and large amounts of renewable energy sources can be faster and more efficiently integrated.

A medium-term hydro power scheduling model based on stochastic dual dynamic programming is customized and used to study the effects from coordination of hydro and wind power production in a transmission constrained area while considering stochastic inflow and wind. The model is used in a case study for a future scenario of a region in western Norway with large potential for small hydro power and wind power development where the system is studied for different levels of transmission and wind power capacity. The main objective of the study is to give a general assessment on the effects of coordination of hydro and wind power in a transmission constrained area including the impact on spillage, revenue, reservoir strategy and grid-utilization.

Results from the case study show that large amounts of wind power can be integrated in a system dominated by storable hydro power, even if the transmission capacity is limited, without significantly increasing the energy loss. Coordination results in a lower reservoir level and a shift in storable hydro power production towards lower power levels which reduces spillage and wind curtailment. The export of energy out of the system increases when coordinating and duration on the transmission lines are shifted towards intermediate levels. Revenue is moved from storable hydro power to run-of-river hydro and wind power as coordination results in moved storable hydro power production to less profitable periods.

Sammendrag

Som en del av innsatsen i å redusere konsekvensene av klimaendringene ved å øke mengden energi fra fornybare energikilder har Norge og andre Europeiske nasjoner forpliktet seg til konkrete mål gjennom EUs fornybardirektiv. For å nå målene i fornybardirektivet har Norge og Sverige inngått et samarbeid om å øke andelen fornybar energi gjennom et felles marked for grønne sertifikater. Både Norge og Sverige har gode forhold for utvikling av mer produksjon av fornybar energi fra vind og vannkraft, men mange av disse energi-ressursene finnes i områder hvor kraftnettet har lav overføringskapasitet. Utbygging av kraftverk i områder hvor overføringskapasiteten er lav representerer en ekstra kostnad ved at nye kraftlinjer må bygges. Behovet for å bygge nye kraftlinjer kan reduseres ved å koordinere produksjon fra vannkraft med magasin og vindkraft slik at vindkraftressursene kan bli raskere og mer effektivt utnyttet.

For å studere effektene fra koordinering av vannkraft og vindkraft i et område med begrenset kapasitet i kraftnettet brukes en sesongmodell for vannkraftplanlegging basert på stokastisk dual dynamisk programmering. Modellen er brukt i en analyse som tar utgangspunkt i en aggregert modell basert på et fremtidig senario for kraftsystemet i Sogn og Fjordane. Området har gode forutsetninger for utvikling av småkraft og vindkraft og flere situasjoner er analysert med forskjellige nivå av nettkapasitet og vindkraftutvikling. Hovedfokuset i analysen er å gi en generell vurdering av hvordan koordinering av vind og vannkraft i et område med begrenset nettkapasitet påvirker flom, inntekt, tappingsstrategi og utnyttelse av kraftnettet.

Resultat fra analysen viser at store mengder vindkraft kan integreres i et system dominert av vannkraft med magasin, selv om overføringskapasiteten er begrenset, uten å føre til store mengder tapt energi. Koordinering resulterer i et lavere magasin-nivå og mer produksjon på lavere effektnivå som bidrar å redusere flom og energitap fra vindkraftproduksjon. Koordinering bidrar til å øke eksporten av energi ut av systemet og flytter effektbruken på linjene mot lavere nivå. Inntekt fra vannkraft med magasin blir flyttet til elvekraft og vindkraft som et resultat av at koordinering fører til flytting av produksjon til mindre lønnsomme perioder.

Preface

This is a master thesis written at the Department of Electric Power Engineering at the Norwegian University of Science and Technology(NTNU) the spring 2016. The main part of this thesis is written in an article format and a sort version of this article is submitted for the 51st International Universities Power Engineering Conference in Coimbra, Portugal.

I would like to thank Martin N. Hjelmeland, Camilla T. Larsen and Magnus Korpås for their help and excellent guidance during the process of writing this thesis. I would also like to thank SINTEF Energy Research for providing data such that the case study could be formulated and studied.

Preparing for and writing this thesis by working on practical problems with real planning algorithms have been a very informative and motivating educational experience. It has been interesting to get a deeper understanding of energy planning and scheduling algorithms and it is a topic i hope to work more on in the future.

Espen Flo Bødal

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1 Introduction

1.1 Thesis Motivation

Coordination of hydro and wind power generation is an increasingly interesting topic as the prices of developing wind power resources has dropped significantly recent years. The topic of coordination has been studied in several papers, also by researchers at NTNU and Sintef. Most of the current papers that focus specifically on coordination of hydro and wind power regards short-term optimization or medium-term studies using simulation models. It is therefore interesting to perform a medium-term study on coordination using a more formal optimization model to supplement the existing studies on the topic.

In the project work leading up to this mater thesis a project report was written related to a project on including reserve markets in hydro power scheduling where a medium-term model based on stochastic dual dynamic programming was used. This model can also be used for studying the effects of coordination of hydro and wind power production and a significant amount of work has gone into modifying it to fit the single area model used in the analysis and other algorithmic changes.

1.2 Layout of Master Thesis

The main part of this master thesis is an article on the effects from coordination of hydro and wind power using a medium-term scheduling model. A short version of the article in this master thesis is shown in Appendix F and submitted for the 51st International Universities Power Engineering Conference in Coimbra, Portugal.

Additional data and results are presented in Appendix A and B respectively while additional data from the inflow modelling is included in Appendix C. Issues related to inflow modelling and tank water usage is discussed in Appendix D. Appendix E shows how not including the increased congestion due to more wind power results in a bad strategy for the case without coordination.

2 Article - "Coordination of Hydro and Wind Power in a Transmission Constrained Area using SDDP"

Coordination of Hydro and Wind power in a Transmission Constrained Area using SDDP

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***Abstract*—In this work we use a production scheduling model based on Stochastic Dual Dynamic Programming to investigate the effects of coordinating hydro and wind power production in a transmission-constrained area. A case study for a future situation with a significant integration of wind power is performed on an aggregated representation of a region in western Norway. Two strategies for hydro reservoir utilization are developed using the SDDP-model, one only considering hydro power and one considering both hydro and wind power. These two strategies are then tested in an out-of-sample simulator with equal conditions so they can be compared properly.**

Results from the case study show that large amounts of wind power can be integrated in a system dominated by storable hydro power, even if the transmission capacity is limited, without significantly increasing the energy loss. Coordination results in a lower reservoir level and a shift in storable hydro power production towards lower power levels which reduces spillage and wind curtailment. The export of energy out of the system increases when coordinating and duration on the transmission lines are shifted towards intermediate levels. Revenue is moved from storable hydro power to run-of-river hydro and wind power as coordination results in moved storable hydro power production to less profitable periods.

NOMENCLATURE

Indices

i	Power plant unit
j	Cut
t	Time-stage

Parameters

$\mu^j_{(t+1)i}$	Dual value of inflow [kNOK/GWh]
π^R	Cost of generation curtailment [kNOK/GWh]
π^T	Tank water cost [kNOK/GWh]
$\pi^j_{(t+1)i}$	Water value [kNOK/GWh]
π^P_t	Spot-price purchase [kNOK/GWh]
π^S_t	Spot-price sell [kNOK/GWh]
D_t	Local load [GWh]
Q_i^{max}	Maximum discharge [GWh]
$T^{P,max}$	Import capacity [GWh]
$T^{S,max}$	Export capacity [GWh]
V_i^{max}	Reservoir capacity [GWh]

Sets

$\mathcal{H}$	Set of cuts
$\mathcal{T}$	Set of time-stages
$\mathcal{U}$	Set of power plants

Variables

ϖ_{ti}	Tank water [GWh]
e^P_t	Energy purchased [GWh]
e^S_t	Energy sold [GWh]
q_{ti}	Energy discharge [GWh]
r_t	Load curtailment [GWh]
s_{ti}	Spillage [GWh]
v_{ti}	Reservoir level [GWh]
z_{ti}	Normalized inflow

Functions

α_{t+1}	Future-value function
I_{ti}	Inflow function

I. INTRODUCTION

As a part of the initiative to reduce the effects of climate change by moving towards an increased share of energy from renewable sources the European Union has passed the Energy Directive which states clear targets for renewable energy development the next decades. As a part of the European Economic Area (EEA) Norway is affected by EU politics and has currently committed to increase the production of renewable energy by 13,2 TWh within 2020 [1]. The main mechanism to increase the production of renewable energy is the green-certificate market shared by Norway and Sweden which is expected to increase investments in hydro and wind power.

The number of wind farms in Norway is low compared to the available resources and as the cost of wind power production has dropped significantly the latest years [2] the interest in wind power has increased. Many wind farm projects have received permits from the authorities but most of these projects remain undeveloped due to low power prices and poor transmission capacity. Recently, the largest onshore wind power project in Europe was pronounced by the Norwegian central coast, summing up to 1000 MW of installed wind power capacity. Following this investment, a significant investment in the transmission grid is due. The grid surrounding these rural coastal areas is often quite weak and large investments in the transmission grid are necessary to be able to benefit from the good wind resources.

In [3] the problem of phasing in wind power in the Norwegian power system is studied for a case in Northern-Norway. The study shows that development of even moderate amounts of the available wind resources will cause a significant drop in the power price, significant transmission congestions, increased marginal transmission costs and increased amounts of spillage. The study concludes that development of transmission capacity should be internalised in the wind power projects and that such an internalization would make many projects in rural areas, with weak grid connections, less cost efficient such that other projects should be prioritized instead.

Currently the Norwegian power production portfolio consists of about 97 % hydro power with a total storage capacity of 84 TWh [4]. Wind power could be faster and more efficiently integrated by taking advantage of the characteristics of storable hydro power. Coordination of hydro and wind power may reduce the need for grid investments by adjusting the hydro power production to utilize the transmission lines more optimally. The advantages and disadvantages of such a coordination needs to be investigated further to assess the socio-economic benefits of such a solution.

Several papers have been published on coordination of hydro and wind power for short-term scheduling. In [5], [6] a short-term scheduling algorithm for coordination of hydro and wind power is developed for bidding in the spot market, the algorithm is applied in a case study and compared to hydro power scheduling without considering wind power. In these papers the hydro power plants and wind power farms are assumed owned by different utilities, hydro power is assumed to have priority on the transmission lines and wind power would be curtailed when the lines are congested. The main conclusions from these papers are that coordination between the hydro power utility and wind power utility is mutually beneficial, reduces wind energy curtailment and improves the utilization of the transmission lines.

In [7] the short-term scheduling algorithm from [5], [6] is expanded to include the regulating market. Furthermore [8] proposes a scheme for splitting the extra value caused by the coordination. All the previous papers focuses on short-term planning and uses fixed end-of-week reservoir volumes in the algorithms and thus purposely neglecting the possible long term effects of the coordination.

Coordination of hydro and wind power has previously also been studied for long- and medium-term scheduling. In [9] and [10] an algorithm for coordination of hydro power and wind power is outlined, the algorithm uses a predefined reservoir strategy for hydro power as input. Depending on which control-strategy is chosen, adjust hydro power production or curtail wind power, the original hydro power strategy is modified or used as is when the system operation is simulated. [10] includes a comprehensive case-study for a region of the power system in Northern-Norway, the study shows that coordination between hydro power and wind power increases the amount of wind power that can be integrated into the system by increasing the utilization of the transmission lines and reducing the spillage. As both of the previously mentioned medium-term studies uses the same simulation method and gives positive results in regards to wind power integration it is interesting to see how these results holds up compared to a more formal optimization method.

A modern state-of-the-art method to solve long- and medium-term optimization problems is stochastic dual dynamic programming (SDDP), this method was introduced for power system applications in [11] and can be used for a wide range of problems. Some of the main advantages with the SDDP algorithm compared to more traditional methods, e.g. the water-value method used in the one area market-simulator model (EOPS) [12] developed by Sintef Energy Research, is that it allows for many state variables and more detailed modelling of the power system while keeping the problem tractable and capturing the dynamic effects between different reservoirs.

In [13], [14] a SDDP-model is developed and used for medium-term hydro power scheduling of multi-reservoir systems, combining SDDP and SDP with a Markov-chain for stochastic representation of the spot-price. A similar model including a linear grid model is used in [15] to model a future case of the Icelandic power system with wind power, pumped-storage hydro power and a cable to the UK. [15] shows that using a fine time resolution and including an internal grid model with linearised power flow equations is important to obtain a realistic solution.

The main objective of this paper is to provide a basic analysis of the effects regarding coordination of hydro and wind power and thus a one-area model where the internal transmission grid is neglected and all the power plants in the area is aggregated into one storable hydro power plant, one run-of-river hydro power plant and one wind power farm serves as a sufficient model.

This paper is organized as follows; Section II gives a brief introduction to the most important features of the SDDP algorithm, other basic modelling features are explained and the LP-formulation for the model is presented. A case study is outlined and results are presented in Section III. Finally, the main conclusions and suggestions for further work are given in Section IV.

II. Method and Modelling

A. Stochastic Dual Dynamic Programming

Hydro power scheduling and many other real-life applications are often significantly affected by uncertainty as future values of parameters are hard to predict e.g. spot-price, inflow and wind-speed. The uncertain data in stochastic models are usually described by $k \in \mathcal{K}$ discrete values with probability ρ_k, different sequences of uncertain data realizations throughout a given number of time-stages forms many possible scenarios and results in a large problem which is hard to solve.

One way of solving a stochastic problem is using a discrete description of the state-variables and Stochastic Dynamic Programming (SDP) [16][17] as in the water-value method. A problem using SDP is that the problem size grows exponentially with the number of state-variables. The exponential growth in problem size causes the solution-time to become too large for problems with detailed Mixed Integer Program (MIP) modelling.

Another way of solving a stochastic problem is by formulating it as a linear problem. A stochastic problem can be formulated and solved as one large special structured linear problem, but to solve most real-life stochastic linear problems decomposition by stage or scenario is used. When decomposing a stochastic linear problem by time-stages a scenario-tree is created as illustrated in Figure 1. Each node, n, in the scenario three represents a linear program (LP) where all nodes has one ancestor node, $a(n)$, and $|\mathcal{K}|$ child nodes, $c(n)$. A common formulation of the linear problems in stochastic optimization is derived using dual theory and Benders decomposition, where cuts are created to provide an approximate description of the future value function [18].

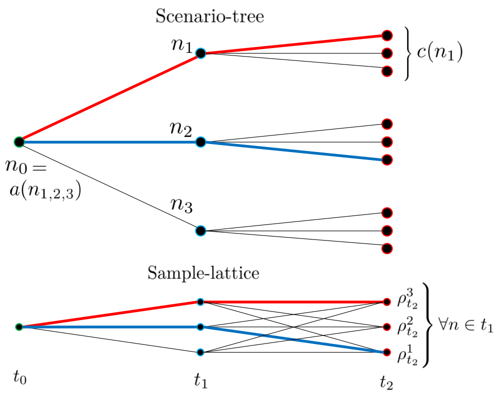

Fig. 1. Example of a scenario-tree and a lattice from stage-wise independent sampling used in SDDP.

A general description of a problem in a node for a multi-stage stochastic problem with cuts is given in Equation (1) to (4). In this case the objective function consists of a term for maximizing the profit in this node, $c_n^T x_n$, but also a future value variable, α_n, which estimates the future value considering decisions made in this node. The future value variable is constrained by the cuts in Equation (4). The cut constraints provide a connection forward in the scenario-tree from node n to the child nodes, $c(n)$, and further into future through cuts until the last stage as the problem is recursively defined. Equation (2) describes constraints that only regards the variables in node n, while Equation (3) describes constraints connecting the node to its ancestor node.

A, W, T, b, h and c are matrices and vectors of parameters, these parameters can be specific for a node within a time-stage or general for all nodes within the time-stage dependent on if they are part of the uncertain data, ξ, or not. x_n is state and decision variables and π_m is the dual variables for constraint 3 in the set of child nodes, $m \in c(n)$. ρ_m describes the probability distribution of the child nodes and Π_m is the set of cuts.

$$Q_n(x_{a(n)}, \xi_n) = \max_{x_n, \alpha_n} \; c_n^T x_n + \alpha_n \tag{1}$$

$$A_n x_n \leq b_n \tag{2}$$

$$W_n x_n \leq h_n - T_n x_{a(n)} \tag{3}$$

$$\alpha \leq \alpha^* - \sum_{m \in C(n)} \rho_m (\pi_m^i)^T T_m (x_n - x_n^*) \quad \forall i \in \Pi_m \tag{4}$$

Cuts can be formulated in multiple ways, the representation in Equation 4 is a single-cut formulation where duals from all child-nodes are summed and weighted by their probability. Another way of formulating the cuts is a multi-cut formulation where cuts are added for each child-node. The cut formulation in Equation 4 also takes advantage of the iterative algorithm used in SDDP by using marginal improvement from the previously obtained solution x^*. Figure 2 illustrates how cuts (solid black lines) created for a certain value of x is used to create an approximate description (red line) of the real future value function (dotted line).

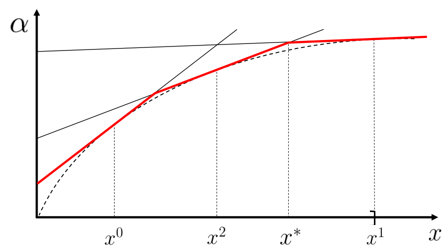

Fig. 2. Illustration of cuts and how they approximate the future value function.

The scenario-tree in a multi-stage stochastic problem can be solved to optimality by solving all nodes in the scenario-tree e.g. using iterative methods like the L-Shaped Method [18]. A problem solving all the nodes in the scenario-tree is that it grows exponentially with the number of time-stages. The exponential growth in problem size causes the solution-time to become too large for problems with a detailed time-resolution or a long time-horizon.

Stochastic Dual Dynamic Programming is a statistically based approximation method for reducing the solution time of multi-stage stochastic problems. In SDDP the scenario-tree is constructed using stage-wise independent data, i.e. the uncertain data have the same discrete probability distribution for all nodes within a time-stage as shown in the sample lattice in Figure 1.

Constructing the scenario-tree by using stage-wise independent data enables Sample Average Approximation (SAA) to be used to approximate the scenario-tree by sampling different paths through the scenario-tree as illustrated by the highlighted paths in Figure 1, significantly reducing the solution-time by not solving all the nodes. It is important to notice that even if the samples can be written as a lattice, due to the stage-wise independent property of the data, the scenario-tree can't as each node represents a unique system state. According to the SAA-theorem the approximation of the problem by sampling from the scenario-tree converges towards the problem described by the complete scenario-tree as the number of samples increases.

Another advantage with SDDP is that the stage-wise independent property of the uncertain data allows cuts to be shared amongst all nodes within a time-stage and thus provide a better description of the future value function.

The SDDP algorithm uses an iterative process with forward and backward runs. In the forward run the LP-problem is

```
Initialize: Some loose initial conditions.
for iterations = 1...max iterations do
   Forward run:
   Sample uncertain data e.g inflow and prices
   for Scenario = 1...S do
      for Time-stage = 1...T do
         Solve the one-stage problem and store the results.
      end for
   end for
   Check bounds:
   if ϵ ≤ |UB − LB| then
      Finished.
   end if
   Backward Run:
   for Time-stage = T...1 do
      for Scenario = 1...S do
         for Inflow Branch = 1...K do
            Solve the one-stage problem in time-stage t and
            store the duals.
         end for
         Use the weighted duals to create a cut in time-stage
         t − 1.
      end for
   end for
end for
```

Fig. 3. A Pseudo-Code for the SDDP Algorithm

solved for all time-stages and solutions are obtained using the current cuts to describe the future value function. In the backward run the solution of the state variables obtained in the forward run is used to create more cuts which is added to the LP-problems to improve the description of the future value function [19]. As the cuts describe the future value function better for each iteration the algorithm eventually to converges towards the optimal solution.

As the cuts provide an upper bound (UB) for the future value function a upper bound for the problem is the objective function in the first stage. A lower bound (LB) is obtained by summing and weighting the value of the obtained solution by its probability for each time-stage. A pseudo-code for the SDDP algorithm is given in Figure 3 and more comprehensive explanations of the SDDP-method are found in e.g. [18] or [19].

B. Inflow modelling

The stochastic parameters in SDDP the must be stage-wise independent but inflow and wind typically exhibit serial correlation which can be accounted for by state-space enlargement. Both wind and inflow have a seasonal pattern, this is first extracted by normalizing the series as shown in Equation 5.

$$z_t = \frac{I_t - \mu_t}{\sigma_t} \tag{5}$$

Where μ_t is the mean and σ_t is the standard deviation of the series in week t obtained from measured or simulated values over a sufficient amount of years. The normalized series are modelled using a vector auto-regressive model of order one, VAR(1). The multivariate time series comprise reservoir inflow, run-of-river (RoR) inflow and wind. Analysis of different inflow models shows that using a vector auto-regressive model over a normal auto-regressive model often gives a better description of the inflow data as there is correlation between inflow and wind [20]. The VAR(1) model is formulated in Equation 6, where $\boldsymbol{\phi}$ is the auto-regressive coefficient matrix for the inflow and wind data and $\boldsymbol{\epsilon}_t$ is a stochastic parameter.

$$\mathbf{z}_t = \boldsymbol{\phi}\mathbf{z}_{t-1} + \boldsymbol{\epsilon}_t \tag{6}$$

The physical value of series j in time-stage t, I_{tj}, is given by Equation 7. Where $\boldsymbol{\phi}_j$ is row j of the autoregressive coefficient matrix.

$$I_{tj}(\mathbf{z}_{t-1}) = \mathbf{z}_t\sigma_{tj} + \mu_{tj} = (\boldsymbol{\phi}_j\mathbf{z}_{t-1} + \epsilon_{tj})\sigma_{tj} + \mu_{tj} \tag{7}$$

As seen from Equation 7 the inflow or wind of a given week, I_{tj}, is dependent on the values in the previous week through the inflow state variables, $\mathbf{z}_{t-1}$, while the stochastic noise parameter, $\boldsymbol{\epsilon}_t$, is independent of previous values. The noise-distribution is descretizised into a number of branches using a fast forward scenario reduction algorithm described in [21].

C. LP-problem

The LP-problem for the power system in time-stage t is formulated in Equation (8) to (15) and consist of the objective function (8), reservoir balances (9), energy balance (10), discharge limits (11), reservoir capacity limits (12), import and export limit (13) (14) and cuts (15).

The objective function in (8) maximizes energy sales from the area under the assumption that the local load has to be covered, this is the same as optimizing the production and can be shown by substituting the energy balance (10) in to the objective function.

$$\hat{\alpha}_t(v_t, z_t) = \max\{\pi_t^S e_t^S - \pi_t^P e_t^P - \pi^R r_t - \sum_{i\in\mathcal{U}} \pi^T \varpi_{ti} + \hat{\alpha}_{t+1}\} \tag{8}$$

s.t.

$$v_{ti} + q_{ti} + s_{ti} - \varpi_{ti} = v_{(t-1)i} + I_{ti}(z_{(t-1)i}) \qquad \forall i \in \mathcal{U} \tag{9}$$

$$\sum_{i\in\mathcal{U}} q_{ti} - e_t^S + e_t^P + r_t = D_t \tag{10}$$

$$0 \le q_{ti} \le Q_i^{max} \qquad \forall i \in \mathcal{U} \tag{11}$$

$$0 \le v_{ti} \le V_i^{max} \qquad \forall i \in \mathcal{U} \tag{12}$$

$$0 \le e_t^S \le T_t^{S,max} \tag{13}$$

$$0 \le e_t^P \le T_t^{P,max} \tag{14}$$

$$\hat{\alpha}_{t+1} \le \alpha_{t+1}^* + \sum_{i\in\mathcal{U}} \pi_{(t+1)i}^j (v_{ti} - v_{ti}^*) + \sum_{i\in\mathcal{U}} \mu_{(t+1)i}^j (z_{ti} - z_{ti}^*) \qquad \forall j \in \mathcal{H}_i \tag{15}$$

In the reservoir balance for a unit i discharge, q_{ti}, and spillage, s_{ti}, is treated as outgoing energy while inflow, $I_{ti}(z_{(t-1)i})$, and tank water, ϖ_{ti}, is ingoing energy. Tank water has to be included due to the VAR(1) model used for modelling the inflow. Negative inflow can occur when the seasonal inflow-profile is at it's lowest, if the reservoir levels are low the problem might become infeasible due to a negative right-hand-side of the reservoir balance. Use of tank water is penalized, π^T, in the objective function as it doesn't represent a real system state.

In the energy balance curtailed load, r_t, discharge and purchased energy, e_t^P, is energy into the system while sold, e_t^S, and locally consumed, D_t, energy is energy out of the system. Load curtailment is penalized, π^R, by the value of lost load in the objective function as it has a high socio-economic cost and is very undesirable. There is a small price difference in the objective function between the price to sell, π_t^S, and purchase, π_t^P, energy to avoid selling and purchasing at the same time.

Transmission is represented by a constant maximum transmission capacity when calculating the strategy for coordination and in the simulator for both cases. When not coordinating, a transmission capacity profile is used in the strategy calculations to account for the reduced transmission capacity from the hydro power point-of-view due to wind power production. The transmission capacity profile is calculated by subtracting the expected wind power production from the transmission capacity limit.

As seen from the reservoir balance (9), reservoir level, $v_{(t-1)i}$, and normalized inflow, $z_{(t-1)i}$, is the state variables connecting the time-stages and thus they are used in the cuts (15). The dual of the reservoir balance, $\pi_{(t+1)i}$, the water value, and the dual of the inflow, $\mu_{(t+1)i}$, from the next time-stage $t+1$ is also used in the cuts. The inflow dual isn't a dual for an actual constraint but is related to the water values as shown in Equation (16).

$$\mu_u^j = \sum_{i \in \mathcal{U}} \phi_{i,u} \sigma_i \pi_i^j \tag{16}$$

D. Initial Reservoir Level and End-Cuts

The strategy is calculated over a period of three years with equal demand and prices each year. As it is normal for the reservoirs to be emptied before the spring flood or flooding in the autumn for most of the cases the first and third year provides a decoupling from the values at each end of the planning period for the strategy in the second year. Thus when studying long-term effects of coordination, the focus is on the second year as it is least affected by the initial reservoir level and end cuts.

E. Simulator

The strategies obtained from the strategy calculations are compared in an out-of-sample simulator, the simulator is similar to the forward run in the SDDP algorithm for the coordination case but with pre-sampled inflow and wind series. The inflow and wind series used in the simulator are pre-sampled using a continuous description of the noise distribution which provides better samples more similar to the underlying data.

To keep an acceptable calculation time the strategy calculations uses a lower number of discrete noise levels and data samples as the main driver of the calculation time is the backward runs where the cuts, i.e. the reservoir strategy, is calculated. The simulator uses a significantly higher number of inflow and wind samples compared to the strategy model which further helps providing a better representation of the possible system states in the scenario-tree.

III. Case Study

A. System modelling

A one-area model is created to represent the grid-constrained area, internal transmission-lines are neglected and power plants are aggregated as illustrated in Figure 4. Three different units are created based on the following categories, storable hydro power, RoR hydro power and wind power. The local load is represented by a deterministic load series based on the average load, while the transmission-lines are modelled as restrictions on the amount of power that can be exchanged with the external power market. To focus on the stochastic properties of inflow and wind a deterministic price is used for power sales to, or purchases from, the external market.

Further division of the power plants based on location would provide a better description of the power system as inflow and wind patterns differ significantly within the area, but to keep the problem size low and focus on the principal effects it is neglected in the analysis.

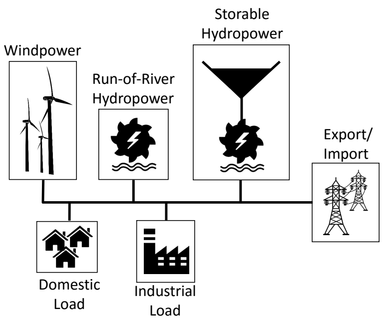

Fig. 4. Illustration of the power system model.

To limit the scope of this analysis and due to the computing resources available a time-step of one week is used. The model in this paper is based on many of the same principals as in [13] and [14], but it is also significantly modified to fit to the area model. No considerations are taken with respect to different ownership of power plants or transmission line priorities as in [5], [6], [7]. As there are no priorities on the transmission lines the flexibility of the storable hydro power plant is used to move production in real-time in the simulator for both strategies but only the coordinated strategy regards wind power in the reservoir strategy calculations.

B. Case system

Sogn og Fjordane is a region in western Norway and the region in the country with the best potential for development of small hydro power. According to the Norwegian Water Resources and Energy Directorate (NVE) the region has about 4.89 TWh of total remaining hydro power resources as of january 2015 [22]. It is also one of the regions in Norway with the best wind power resources according to a wind power resource analysis on behalf of NVE, while the regions in northern Norway are the best in the country [23]. Currently there are only one wind farm in the region with a capacity of 23 MW and an approximate 59 GWh of yearly production, but a lot of permits are given for new projects. About 750 MW of new wind power projects are currently under consideration and most of them have a final permit.

Limited grid capacity has restricted the development of many hydro and wind power projects in the region [24], but a new 420 kV line is due to be operational within the near future. Many small hydro power projects are expected to start construction quickly as more transmision capacity becomes avaliable and as renewable powerplants needs to be operational within the end of 2021 to take advantage of the green-certificate system [1], [25].

It's difficult to predict how the system will develop in the future with good accuracy but by using data from [26] and [24] two different scenarios are developed for the production portfolio in 2030. Table I includes the estimated power system production capacity and energy for 2011 and 2014 [26], [24]. The analysis in [24] includes low, moderate and high scenarios for the power system in 2030, where the moderate and high scenarios are included in Table I. In 2014 the estimated remaining hydro power resources was about 5.3 TWh, and the moderate and high scenarios equals developing about 68% and 92% of the remaining hydro power resources.

The analysis of the power system in [26] provides a more detailed description of the hydro power system in 2011 by storable and RoR hydro power. By using the detailed description of the power system in 2011, more detailed scenarios are created for 2030 as shown in Table II. These scenarios result in an increase of the installed capacity for RoR hydro power and storable hydro power by 200-250% and 30-36% relative to the 2011 level which illustrates the huge potential for development of RoR hydro power in the region.

While the future power is distributed equally between storable and RoR hydro power, storable hydro power is allocated with a higher amount of future capacity as it usually has a higher capacity to energy ratio compared to RoR hydro power. It is also worth noticing that for both the moderate and high case the total power to energy ratio increases.

Using the future energy scenarios and assuming a future degree of regulation (Reservoir Capacity/Yearly Inflow) at 0.71, same as in 2011 [26], the aggregated reservoir capacity is estimated to be 9 730 GWh and 10 170 GWh for the moderate and high scenario respectively.

Inflow, wind and load records for the case study are provided by SINTEF Energy Research and adjusted to fit the energy quantities in the specified scenarios. Wind records used in this paper are obtained from re-analysis data which is adjusted for regional effects [27]. The inflow and wind energy profiles are shown in Figure 5 for the case with high hydro power development and 1000 MW installed wind power

TABLE I
TOTAL POWER AND ENERGY IN SFJ POWER SYSTEM.

	2011	2014	2030-Mod	2030-High
Power [MW]	3 743	4 139	5 500	5 900
Energy [GWh]	12 601	13 900	17 500	18 750

TABLE II
PROGNOSIS FOR THE POWER SYSTEM IN 2030.

	Storable Hydro Power		RoR Hydro Power	
	Mod	High	Mod	High
Power [MW]	4 360	4 570	1 140	1 330
Energy [GWh]	13 700	14 320	3 800	4 430
Future Power Share	0.57	0.56	0.43	0.44
Future Energy Share	0.50	0.50	0.50	0.50
Power Increase	30%	36%	199%	249%
Energy Increase	22%	27%	181%	227%

capacity.

The inflow profiles for storable and RoR hydro power differ significantly from each other as most of the hydro power reservoirs are located at a higher altitude than the RoR hydro power. Due to the high altitude the inflow for storable hydro power is small in the winter as most of the precipitation is snow, a significant peak in the inflow-profile occurs as the snow stored throughout the winter melts in the spring.

Future local load in the region it is very dependent on the development of the Energy Intensive Industry (EII) which consume about 75% of the total load of 6000-7000 GWh. The estimated annual growth of domestic energy consumption is 0.9% a year. Estimations for local load in 2030, assuming no shut down of EII, range between 7000 GWh and 9000 GWh dependent on further EII development [24]. In this paper a low level of local load development is assumed and a local load at 7000 GWh is used.

The historic price-profile from the NO3 area for 2015 is used as shown in Figure 6. The 2015 price-profile has a lower summer price than previous years which is the expected

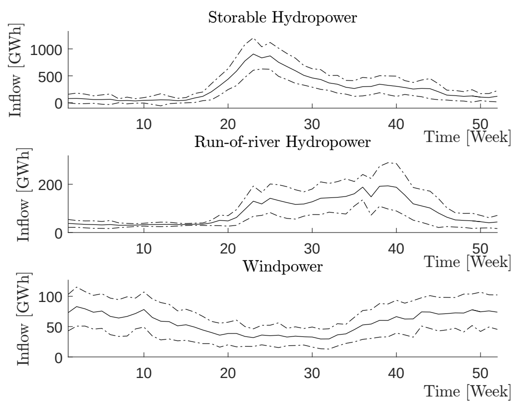

Fig. 5. Aggregated inflow profiles for Sogn og Fjordane.

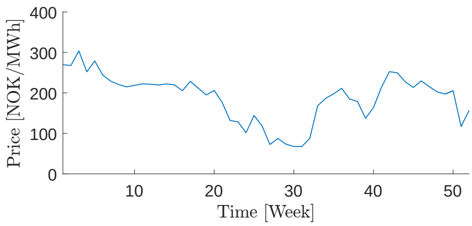

Fig. 6. The price-profile of the power price in 2015 which is used in the analysis.

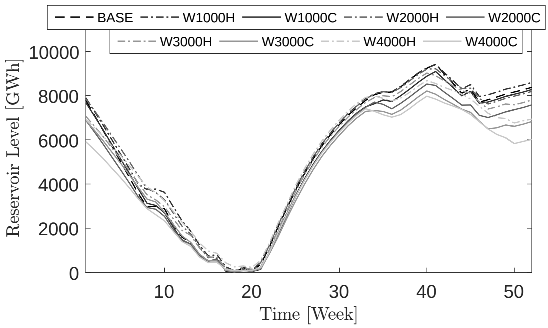

Fig. 7. Reservoir level for storable hydropower in the second year of the planning period for different levels of wind power integration.

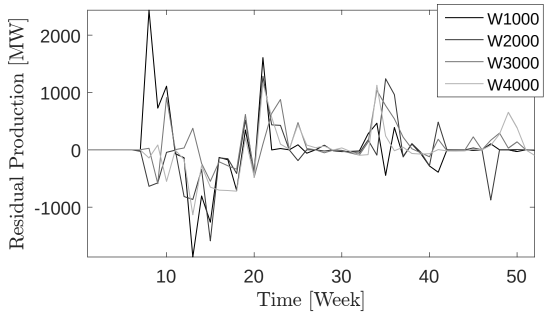

Fig. 8. Residuals for storable hydro power production for the second year of the planning period and different levels of wind integration.

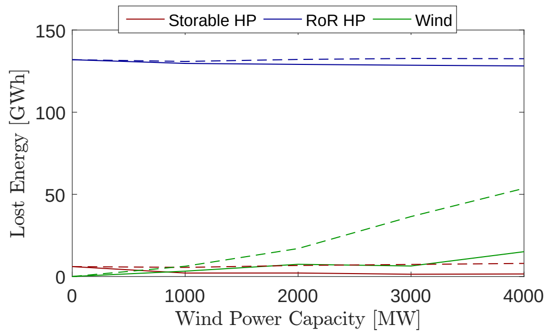

Fig. 9. Lost energy in the second year of the planning period for different levels of wind power integration. Hydro (dashed lines) and Coord (solid lines).

characteristic of the future price profiles.

C. Results

The high scenario for the hydro power system in 2030 is analysed for the two different strategies and represented by the following notations:

- Hydro (H): Optimization of hydro power production.
- Coord (C): Coordination of hydro and wind power production.

As the simulator uses 1000 inflow scenarios most of the plots are mean values of these scenarios. High resolution duration curves are created by compressing all 1000 scenarios horizontally.

1) Wind Power Analysis: The system is analysed with different amounts of wind power ranging from 0 MW in the base case to 4000 MW, a transmission capacity of 4000 MW is used as it preserves most of the flexibility of the storable hydro power by allowing it to produce at maximum capacity while still providing a small level of congestion in the base case.

As shown in Figure 7 the reservoir level is reduced in the winter as more wind power is included regardless of coordination or not. Coordination results in significantly larger reductions in the reservoir level. A lower reservoir level during the winter allows the storable hydro power to adjust the production dependent on the highly intermittent wind power without risking additional spillage.

A lower reservoir level leaves less water in the reservoir for the high prices in the end of the winter-period (week 10-20) before the spring flood. The lower reservoir level results in less production in the late winter period as shown from the residuals for production in Figure 8, where residuals are defined as the value of Coord subtracted by the value of Hydro. Coordination results in a higher production in the start (week 20) and end (week 35) of the reservoir filling period to get a lower reservoir level.

Figure 9 shows how the wind curtailment increases with the amount of wind power in the system when not coordinating while no changes in curtailment of RoR hydro power and spillage from the reservoirs are observed. The increased amount of wind power curtailment when not coordinating are low compared to the total amount of energy from the integrated wind power.

Without coordination and when 4000 MW wind power is included, which is the same as the total transmission capacity, the level of wind power curtailment is only 0.46 % of the total wind power production. The low level of wind power curtailment is a result of regional effects for wind which gives wind power a more even production pattern and the flexibility of the hydro power system to move production in real-time to avoid spillage.

Curtailment of RoR hydro and wind power is a result of

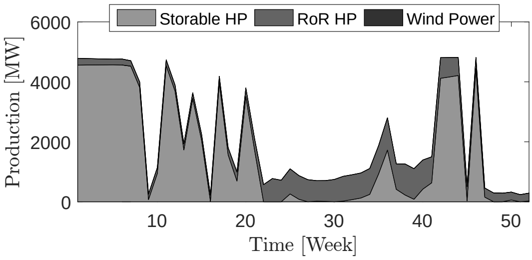

Fig. 10. Total production for base case in the second year of the planning period.

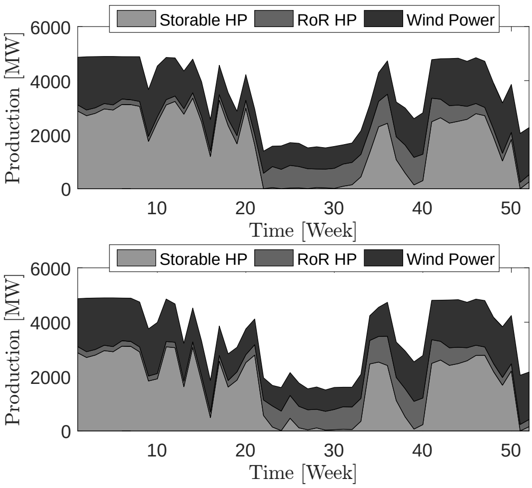

Fig. 11. Total production for the case with 4000 MW installed wind power capacity in the second year of the planning period, Hydro (top) and Coord (bottom).

spillage from the reservoirs as the marginal cost of generation for storable hydro power is zero when water spills and the inflow can't be stored for future production. Coordination reduces the amount of spillage from the reservoirs by reducing the reservoir levels, less spillage from the reservoirs results in significantly less wind power curtailment as more wind power is included.

As shown in Figure 10 the storable hydro power production in the base case is high in some specific periods with good prices, especially in the beginning of the year (week 0-10) where the prices are best. The production pattern for storable hydro power is significantly affected by an increasing level of the wind power integration as wind power has a high level of production in the winter period. Comparing the total production in the base case in Figure 10 with the case where 4000 MW wind power is included in Figure 11, shows how the increasing energy surplus is forcing the storable hydro power to distribute the production more evenly throughout the year as the transmission capacity is limited.

Increasing the amounts of wind power in the system de-

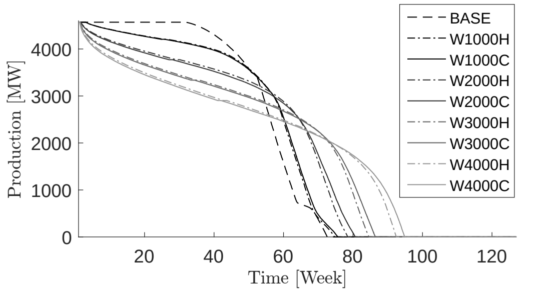

Fig. 12. Duration of storable hydro power production based on the three year planning period.

TABLE III
COMPARISON OF TRANSMISSION FOR THE PLANNING PERIOD.

	Wind Power [MW]	1000	2000	3000	4000
Hydro	Export [TWh]	44.175	51.950	60.220	68.769
	Import [TWh]	1.307	0.380	0.166	0.083
	Congestion[%]	32.51	36.94	43.03	49.77
Coord	Export [TWh]	44.300	52.041	60.397	68.968
	Import [TWh]	1.278	0.388	0.160	0.085
	Congestion[%]	32.26	37.04	42.41	49.70
Diff.	Export [%]	0.28	0.18	0.29	0.29
	Import [%]	-2.20	2.12	-3.26	1.67
	Congestion[%]	-0.25	0.09	-0.62	-0.07

creases the hours of storable hydro power generation at high power levels regardless of coordination or not as shown in Figure 12. Coordination results in a small shift in production from high to lower levels and a increase in total production for storable hydro power as the spillage is reduced. The moved storable hydro power production to the start and end of the reservoir filling period due to coordination explains the shift towards lower power levels as these periods have significant RoR hydro power production in addition to wind compared to the late winter, as shown in Figure 11.

As more wind power is integrated in the system the level of congestion ranges between 32.3% and 49.7 % of the year as shown from Table III. The total export of energy from the area throughout the planning period is higher when coordinating as

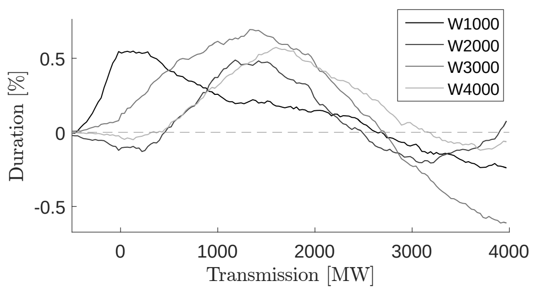

Fig. 13. Differences in duration, Coord subtracted by Hydro, on different transmission levels as a percentage of total duration.

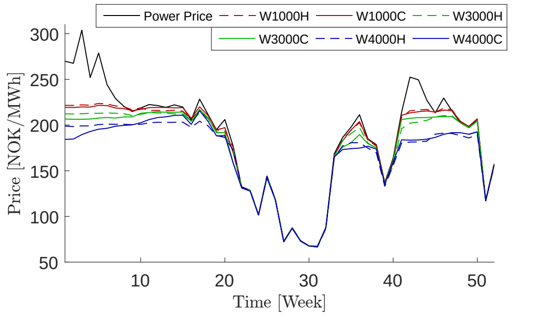

Fig. 14. Dual value for the energy balance for the second year of the planning period.

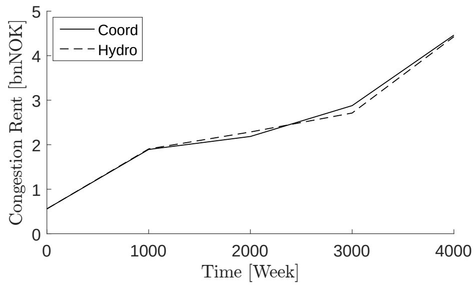

Fig. 15. Congestion rent for different levels of wind power integration.

TABLE IV
COMPARISON OF TOTAL REVENUE FOR THE PLANNING PERIOD.

	Wind Power [MW]	1000	2000	3000	4000
Hydro	Storable HP [bnNOK]	9.953	9.840	9.666	9.484
	End value water[bnNOK]	1.892	1.904	1.956	1.977
	RoR HP [bnNOK]	2.190	2.190	2.190	2.190
	Wind [bnNOK]	1.763	3.524	5.279	7.033
Coord	Storable HP [bnNOK]	9.967	9.813	9.650	9.450
	End value water [bnNOK]	1.862	1.892	1.930	1.954
	RoR HP [bnNOK]	2.190	2.191	2.191	2.191
	Wind [bnNOK]	1.764	3.527	5.288	7.048
Diff.	Storable HP [%]	0.14	-0.28	-0.17	-0.35
	End value water [%]	-1.58	-0.61	-1.32	-1.18
	RoR HP [%]	0.03	0.04	0.05	0.04
	Wind [%]	0.08	0.10	0.18	0.21

shown by the differences in Table III, defined as percentage differences from Hydro to Coord. The higher export when coordinating is a result of more production as spillage and curtailment of energy is reduced. Transmission is moved from high to intermediate levels when coordinating as shown by the difference in duration in Figure 13. The shift in transmission towards intermediate levels is a result of less water in the reservoir, and thus less production, in the end of the winter when the prices are good an RoR hydro power inflow is low. The shift in duration to intermediate levels on the transmission lines are small compared to the total export.

Figure 14 shows the dual value of the energy balance which is the marginal cost of production for the system. The marginal cost of production is set by the price of the external market and the storable hydro power which has the ability to save energy for later periods. If no congestion is present the price is set by the external market, congestion results in a marginal cost of production equal to the opportunity cost of producing energy later, the water value, as both RoR hydro and wind power has zero marginal cost of production.

When using area pricing for congestion management the marginal cost of production in the area represents the area price, the area price indicates congestions in three areas in Figure 14 as it differs from the price of the external market. More wind power in the system results in more congestions and reductions in the area price for the autumn and winter period. The reductions in the area price are larger for the autumn and early winter than for the late winter as the level of wind power integration increases, this is a result of the increased production and reduced water value in this period to reduce the reservoir level.

The dual value for the export constraint represents the value of a marginal increase in transmission capacity and is the difference between the area price and the price of the external market. Differences in the transmission duals and area prices for the two strategies are similar to the differences in production observed from the residuals in Figure 8. Coordination results in higher transmission duals in the start (week 20) and end (week 35) of the reservoir filling period, while not coordinating gives higher duals in the end of the winter (week 10-20).

To quantify the socio-economic costs related to congestions in the different cases the congestion rent is calculated by multiplying the transmission dual with the energy production. The congestion rent is shown in Figure 15 and only small differences and no obvious trend in the congestion rent is observed as more wind power is included.

Table IV shows how the revenue from storable hydro power is reduced for both strategies as more wind power is included in the system. More wind power results in more congestion during the autumn and winter when the prices are high and storable hydro power has to move production to other periods with lower prices.

Coordination results in a shift in revenue from storable hydro power to RoR hydro and wind power as more storable hydro power production is moved to less profitable periods to reduce the reservoir level and energy loss. The shift in revenue from storable hydro power to wind power increases with the level of wind power integration. The lost revenue for storable hydro power due to coordination is small compared to the lost revenue due to the increased congestion.

As seen from the system profit in Table V the increase in RoR hydro and wind power revenue does not completely compensate for the lost revenue from storable hydro power. This is not as expected as previous studies on coordination shows an increased total profit, the differences in total profit are small and shows no clear trend as the amount of wind power increases. The negative difference in total profit might be a result of the inflow model where some tank water usage

TABLE V
PROFIT FROM POWER EXCHANGE FOR THE PLANNING PERIOD.

Wind Power [MW]	1000	2000	3000	4000
Hydro [bnNOK]	11.754	13.415	15.049	16.643
Coord [bnNOK]	11.740	13.381	15.018	16.602
Diff [%]	-0.116	-0.258	-0.209	-0.249

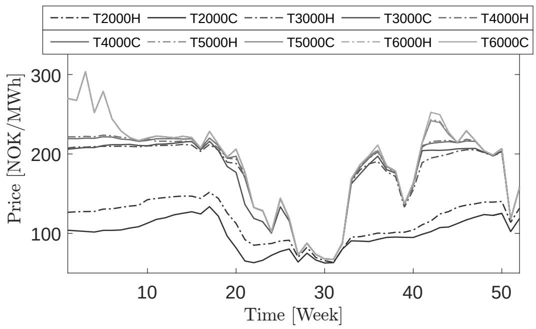

Fig. 16. Dual value of energy balance for the second year of the planning period.

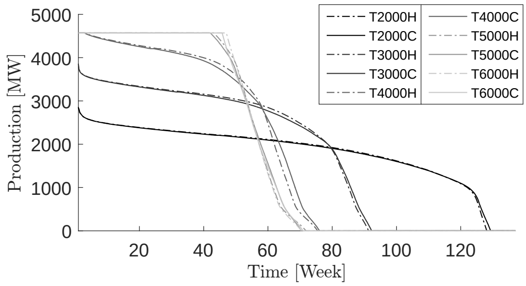

Fig. 17. Duration of storable hydropower production based on the three year planning period.

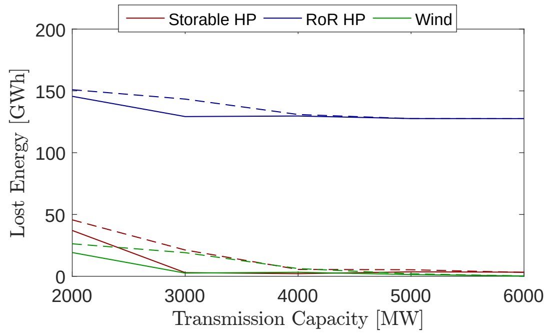

Fig. 18. Lost energy for the second year of the planning period and different levels of transmission capacity. Hydro (dashed lines) and Coord (solid lines).

is forced as the reservoir capacity of the RoR hydro and wind power plants are zero. The forced tank water usage affects the strategies differently as wind power is only included in the strategy when coordinating. This issue is reduced by using different tank costs for storable hydro power than for RoR hydro and wind power, but should be further improved in future work.

2) Transmission Capacity Analysis: A short analysis is performed with different transmission capacities ranging from 2000 MW to 6000 MW while 1000 MW wind power is included. This is a more realistic level of wind power integration for the case system as the total amount of known plans for wind power projects have a total capacity of about 750 MW.

The area prices in Figure 16 shows that transmission capacities over 5000 MW results in area prices equal to the price of the external market as there are no congestions. When the transmission capacity is reduced to 3000-4000 MW there are three periods of significant congestion very similar to the cases in Figure 14. Transmission capacities under 2000 MW results in extreme levels of congestion where the system is congested most of the year.

The transmission capacity significantly affects the operation of storable hydro power as shown in Figure 17. If the transmission capacity is below 4000 MW the ability of the storable hydro power to produce at maximum capacity is limited and in practice the maximum power is reduced forcing the storable hydro power to distribute the production more evenly throughout the year. Coordination results in a small shift in production from high to lower levels, this effect is reduced with the transmission capacity as the ability to move production is reduced.

The amount of lost energy due to spillage or curtailment increases with the level of congestion as shown in Figure 18. Coordination shows promising potential as an alternative to increasing the transmission capacity in terms of reducing the energy loss. In Figure 18 coordination has about the same effect of reducing the energy loss as a 1000 MW transmission capacity upgrade from 3000 MW to 4000 MW.

While coordination has the potential to reduce energy loss it is important to have sufficient transmission capacity to keep the flexibility of the storable hydro power. When the transmission capacity is only 2000 MW and the level congestion is extreme and the system loses the flexibility associated with the storable hydro power and the advantages of coordinating.

IV. Conclusion And Further Work

A future scenario for the power system in a region in Norway has been formulated and used to study coordination of hydro and wind power. Results from the case study shows that a system dominated by storable hydro power can integrate large amounts of wind power without significantly increasing the amount of lost energy even if the transmission capacity is limited.

Coordination of hydro and wind power results in a lower reservoir level which reduces spillage from the reservoirs and wind power curtailment. Introducing more wind power to the system shifts the duration of storable hydro power production towards lower power levels regardless of coordination or not, coordination contributes further to shift the duration towards lower levels as production is moved to periods with higher RoR hydro power inflow.

As more wind power is introduced the congestion in the autumn increases. The area price is significantly reduced in this period as a result of lower water values and increased production. The increased total production due to reduced energy loss results in more total export and the change in production pattern results in a small shift in transmission towards intermediate power levels.

Revenue from storable hydro power is shifted to RoR hydro power and wind power when coordinating as storable hydro power production is moved to less profitable periods, the shift in revenue increases with the level of wind power integration. A small negative result is observed in terms of total system profit but might be related to tank water issues and shows no clear trend as more wind power is included.

Coordination serves as a good alternative to increasing the transmission capacity in terms of reducing the lost energy from wind power curtailment. Sufficient transmission capacity is needed to be able to take advantage of the flexible properties of the storable hydro power to move energy from one period to another.

A. Further Work

Suggestions for further work is:

- Improve the inflow model to reduce the impact of tank water by using different noise distributions for different seasons.
- Analyses with a more detailed model including internal transmission constraints and a more detailed description of the generation in the area, as in [15].
- Introduce price uncertainty by using a model where price is represented by a Markov-chain and the cut generation in the SDDP algorithm is supplemented with SDP.

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A Additional Data

Table A.1 gives an overview of wind farm projects in the region which have applied for permits from NVE as of march 2016. Not all of these wind farms would be connected to the grid in Sogn og Fjordane but it gives a good basis for estimating the wind power potential in the region.

Table A.1: Possible future wind power farms in Sogn og Fjordane. Source:NVE.

Wind power farms	**Power [MW]**	**Energy [GWh]**	**Final Permit**
Guleslettene	160	480	Yes
Dalsbotnfjellet	150	450	Yes
Ulvegreina	138	414	Yes
Bremangerlandet	80	240	No
Sandøy	75	225	No
Lutelandet	45	135	Yes
Hennøy	35	105	Yes
Vågsvåg	24	72	Yes
Okla	21	63	Yes
Testområde Stadt	10	30	Yes
Lutelandet testanlegg	10	30	Yes
Mehuken 3	3	13	Yes
Sum	755	2265	

Figure A.1 shows the mean and standard deviation of the load profile used in the analysis, the load data is provided by Sintef Energy Research and is adjusted to fit the estimated future load at 7000 GWh.

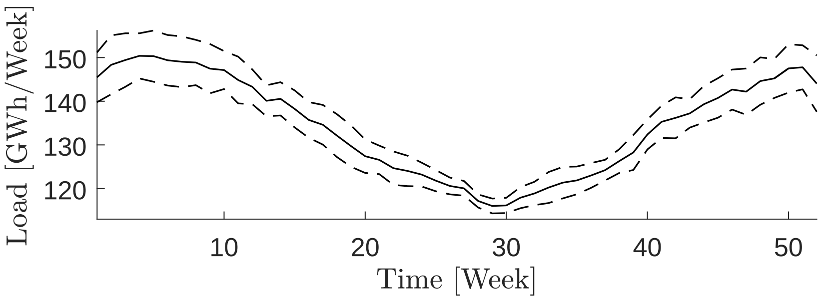

Figure A.1: Load profile by mean and standard deviation.

Parameter	Value
Time Stages	156
Number of Scenarios	100
Backwards inflow samples	9
Max Iterations	12
Rationing Cost [$kNOK/GWh$]	1E6
Tank Cost [$kNOK/GWh$]	930/310
Solver	Gurobi

Table A.2: Parameters used in the SDDP model.

Table A.2 shows the parameters used in the SDDP-model, several different values of the parameters was tested but 100 scenarios and 9 inflow branches resulted in a good trade-of between the problem approximation and calculation time.

B Additional Results

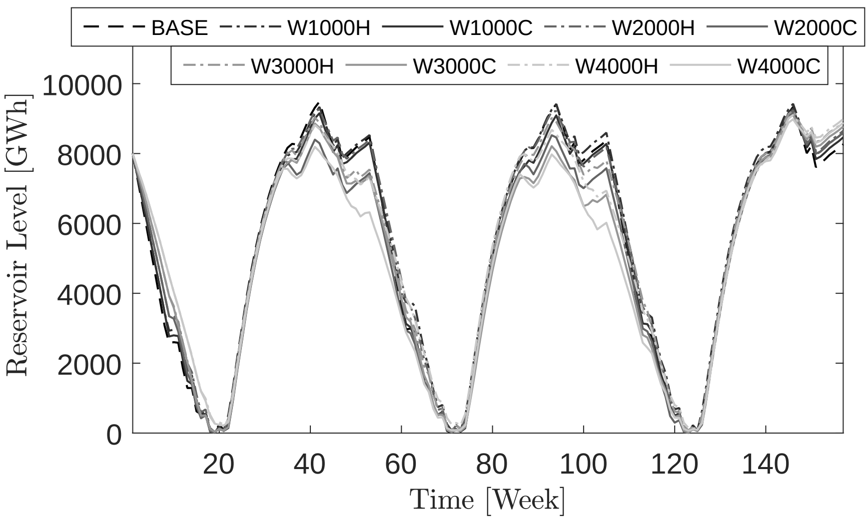

Figure B.1: Reservoir strategy for the entire planning period.

Figure B.1 shows the mean reservoir level for the entire planning period and different levels of wind power integration. The first and second year of the planning period are significantly affected by the start and end values while week 20 and 120 provides a decoupling from start and end of the planning period for the second year as the reservoir is emptied.

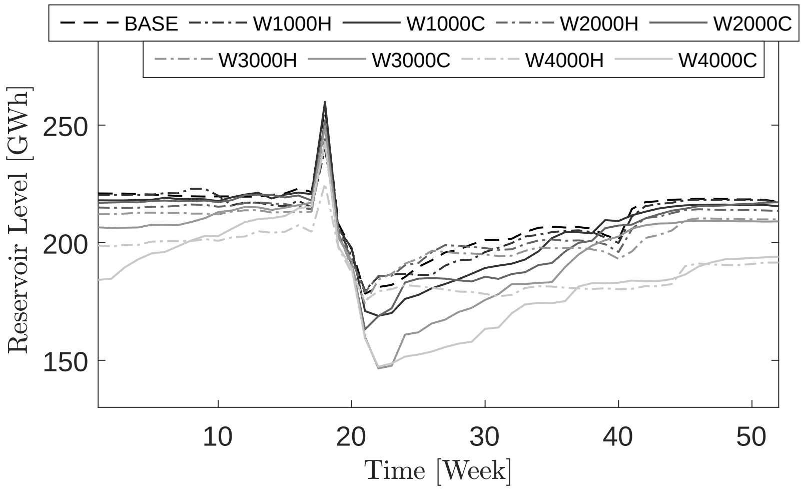

Figure B.2: Water values for the second year of the planning period.

Figure B.2 shows the dual value of the reservoir balance, the water value, for different levels of wind power integration. Some effects of tank water is observed in week 18.

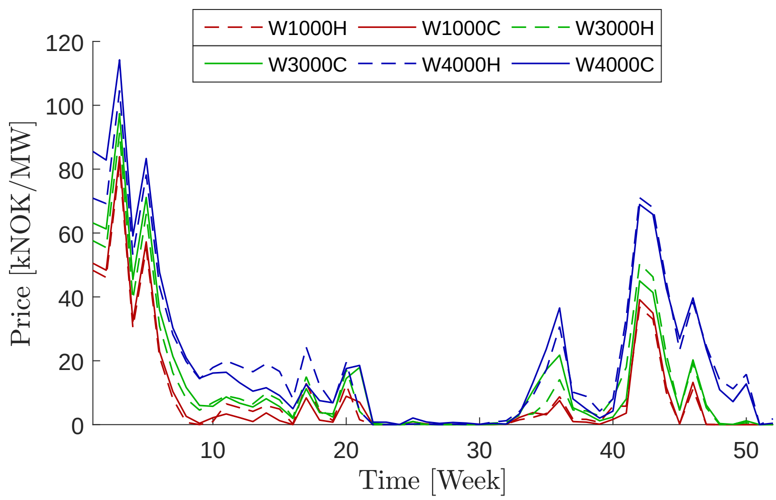

Figure B.3: Dual value of the export constraint for the second year of the planning period.

The dual value of the export constraint is shown in Figure B.3 and is the difference between the area price and the price of the external market.

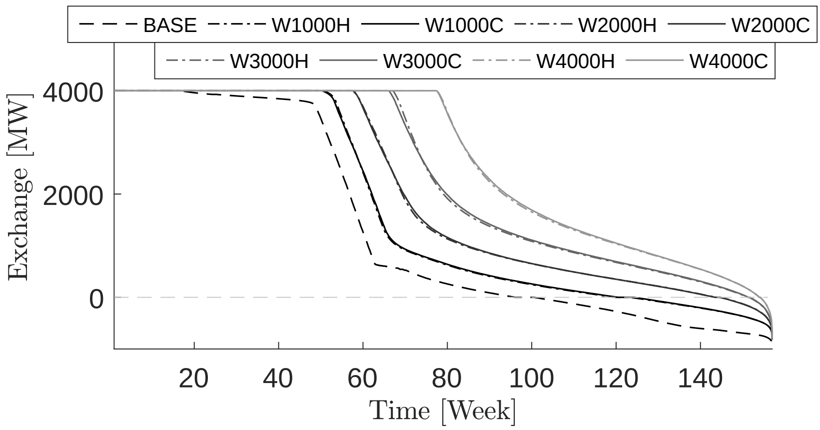

Figure B.4: Duration of exchange for different levels of wind power integration based on the three year planning period.

The duration of exchange on the transmission lines are shown in Figure B.4, a small shift in duration from high to intermediate levels are observed when coordinating.

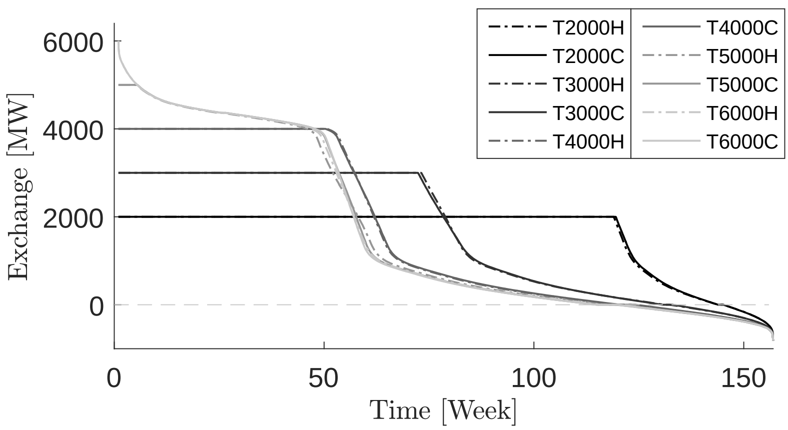

Figure B.5: Duration of exchange for different levels of transmission capacity based on the three year planning period.

Figure B.5 shows the duration of exchange on the transmission lines for different levels of transmission capacity. A transmission capacity at 2000 MW results in a extreme level of congestion where the system is congested most of the year.

C Inflow Modelling

The normalized inflow series based on the data from Sintef Energy Research is shown in Figure C.1.

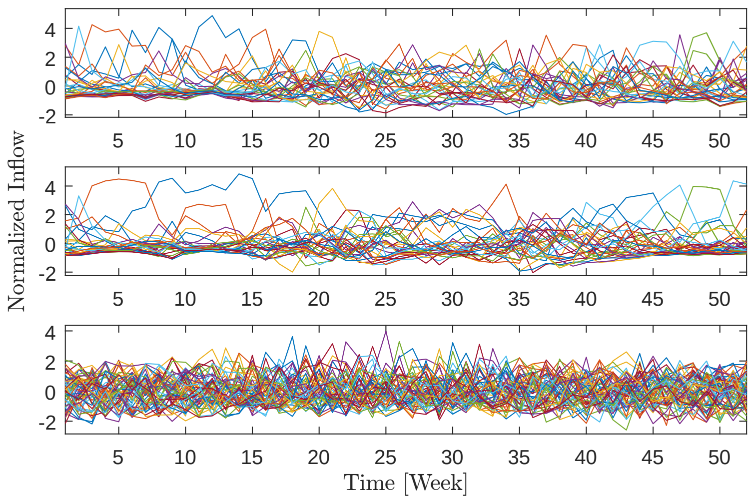

Figure C.1: Normalized inflow data. Storable hydro power (top), RoR hydro power (middle) and wind power (bottom).

In the current implementation of the SDDP-model the same noise distribution is assumed for each time-step throughout the planning period i.e. the inflow data is assumed to be independent and identically distributed (IID). As observed from Figure C.1 this isn't a very good representation for the noise of the inflow series for storable hydro power and RoR hydro power as the noise differ significantly from the winter period with low inflow to the period with high inflow in the summer. The wind energy record also shows a slightly different noise distribution in the summer period compared to the winter.

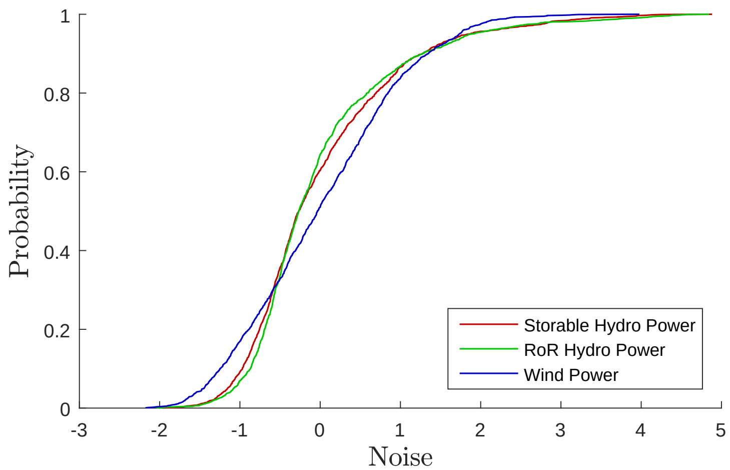

Figure C.2: Cumulative noise distribution function for the different inflow series.

The cumulative distribution of the noise used to sample the inflow series for the out-of-sample simulator is shown in Figure C.2. The normalized inflow series created for the simulator is shown in Figure C.3.

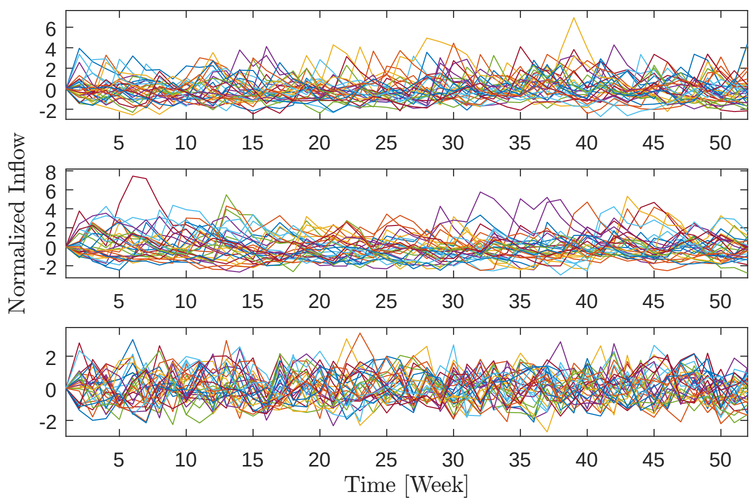

Figure C.3: Normalized inflow series created for simulations. Storable hydro power (top), RoR hydro power (middle) and wind power (bottom).

When fitting the inflow and wind data to the VAR(1) model the autoregressive coefficient matrix shown in Equation (C.1) is obtained, the record order are storable hydro power, RoR hydro power and wind power.

$$\boldsymbol{\phi} = \begin{bmatrix} 0.5737 & 0.0055 & 0.0549 \\ 0.0590 & 0.6960 & 0.0396 \\ -0.0063 & 0.1359 & 0.1787 \end{bmatrix} \tag{C.1}$$

Equation (C.1) clearly indicates a stronger sequential correlation for the inflow records than for the wind power record, but also a significant relationship between inflow to RoR the previous week and the wind power resource in the current week through $\phi_{3,2} = 0.1359$.

D Additional Discussion

Issues related to tank water is observed which should be further investigated in future work. Tank water is needed to ensure feasibility due to the vector auto-regressive model used to model the normalized inflow and wind series. Usage of tank water is forced in some periods for RoR hydro and wind power as both are modelled with zero reservoir volume and can't regulate the reservoir level to avoid tank water.

The usage of tank water affects the cuts differently for the two strategies as wind only is included in the cuts when coordinating. When modelling RoR hydro and wind power with the same tank water costs (1000 NOK/MWh) as storable hydro power a negative trend in the total profit for the system is observed for coordination compared to not coordinating as more wind power is integrated as shown in Table D.1.

Table D.1: Profit from power exchange for the planning period while keeping tank water costs equal for all power plants.

Wind Power [MW]	1000	2000	3000	4000
Hydro [bnNOK]	11.749	13.413	15.057	16.617
Coord [bnNOK]	11.751	13.400	14.988	16.494
Diff [%]	0.024	-0.102	-0.459	-0.736

Using a higher tank water cost for the storable hydro power compared to the RoR hydro and wind power reduces the negative trend in profit for coordination. The tank water cost for RoR hydro and wind power is set to 310 NOK/MWh while the tank water cost for storable hydro power is set three times as high at 930 NOK/MWh.

As shown in Table D.2 the profits change, especially for coordination, when using different tank water costs compared to keeping the tank water costs the same for all power plants. In total the changes are positive, indicating better reservoir strategies, and there are no longer a negative trend in the total profit for coordination. Lowering the tank water cost for all power plants to 310 NOK/MWh doesn't have any significant effect on the total profits from exchange compared to keeping the prices at 1000 NOK/MWh.

Table D.2: Profit from power exchange for the planning period while using a lower tank water cost for RoR hydro and wind power.

Wind Power [MW]	1000	2000	3000	4000
Hydro [bnNOK]	11.754	13.415	15.049	16.643
Coord [bnNOK]	11.740	13.381	15.018	16.602
Diff [%]	-0.116	-0.258	-0.209	-0.249

Using different tank water costs significantly reduces the tank water usage for storable hydro power when coordinating as the wind power integration increases as shown in Figure D.1. Different tank water costs have little to no effect on tank water usage for the strategy without coordination. There are still some differences in tank water usage when using different tank costs which might explain the negative differences in profit from power exchange, future work should make efforts to reduce these differences further.

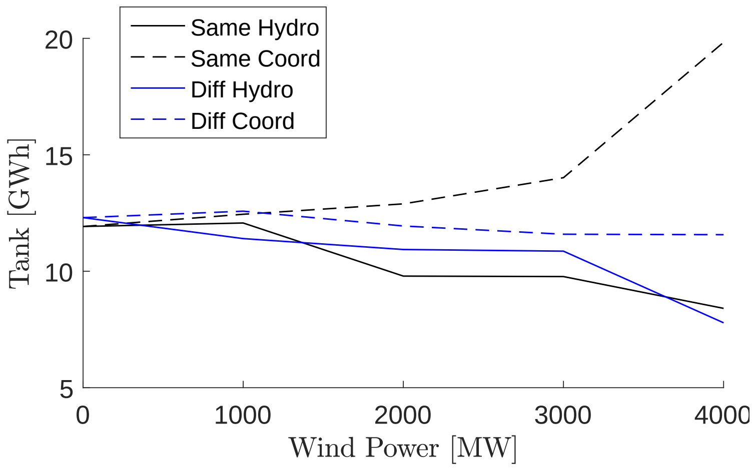

Figure D.1: Tank water usage for storable hydro power during the planning period while using different (Diff) or the same (Same) tank costs.

One way of further reducing the usage of tank water for future work could be to use different noise distributions in each step or in different seasons for the inflow model. Using a noise distribution divided into seasons would result in less tank water usage as the noise distribution is shifted towards positive values in periods with low inflow or wind.

The advantages of using the SDDP method for solving this case system is significantly reduced as the system only has a few state variables and only one reservoir. The water-value method would serve as a sufficient method for solving the problem analysed in this work and would have solved the problems regarding tank water. However, by using the SDDP method on the aggregated level the issues regarding tank water usage is highlighted, in future work the impact of tank water on the strategies could be studied by comparing with strategies obtained by using the water-value method. Using the SDDP method in the analysis allows the model to be easily extended to a more detailed model with more reservoirs for future work.

E Transmission Capacity

Wind power is excluded from the planning when not coordinating, if a constant transmission capacity is used it results in a bad strategy as the transmission capacity in certain periods would be significantly reduced, from the storable hydro power point-of-view, when wind is later included in the simulator. To adjust for the unrealistic transmission capacity when creating the reservoir strategy, the mean wind power production is subtracted from the transmission capacity in the export constraint. Results from planning the reservoir strategy for storable hydro power without considering the increased level of congestion due to the increased energy surplus are shown below.

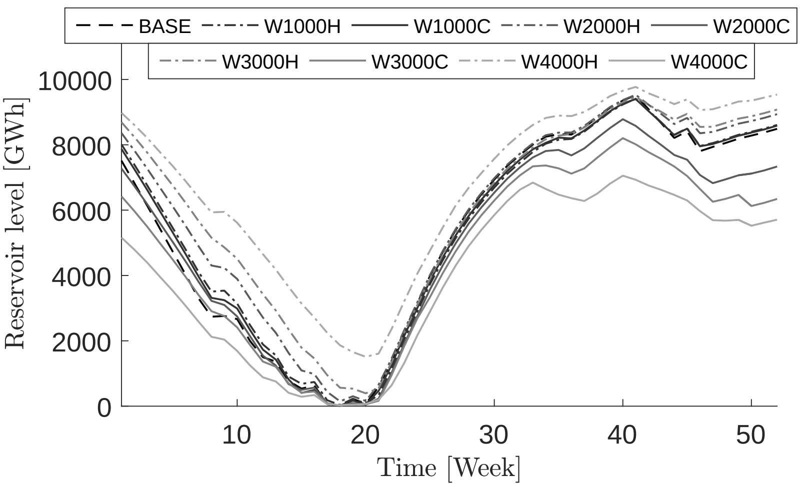

Figure E.1: Reservoir strategy for the second year of the planning period when keeping constant transmission capacity.

Figure E.1 shows how the reservoir level increases when not coordinating as more wind power is included, this is a result of not considering the increased level of congestion due to the increased energy surplus when planning the reservoir strategy.

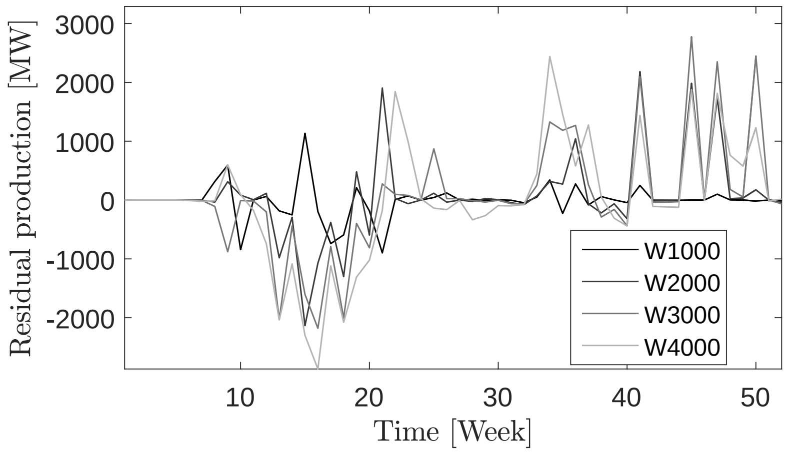

Figure E.2: Residual production in the second year for the base case .

The residuals for the production of storable hydro power is shown in Figure E.2 where a stronger difference in production is observed in the late winter period as the reservoir level increase when not coordinating and more energy is produced in the late winter to reduce the reservoir level before the spring flood.

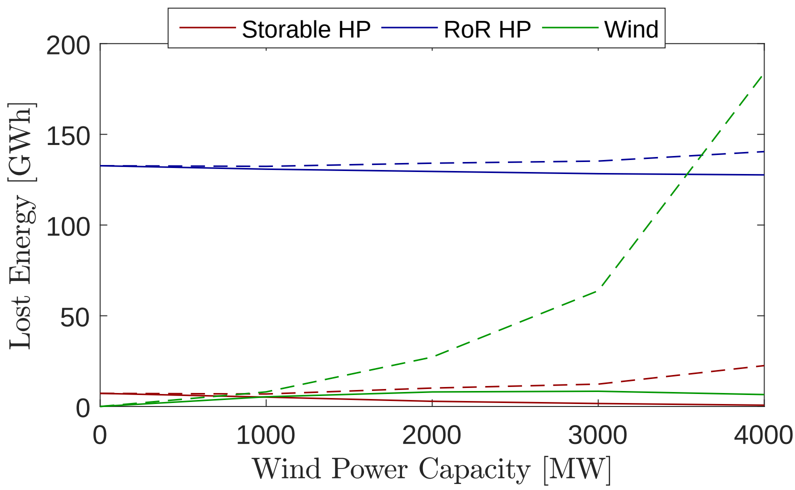

Figure E.3: Lost energy from spillage and curtailment for the second year of the planning period.

Figure E.3 shows how the amount of lost energy is significantly larger for the uncoordinated case. The level of wind power curtailment is three times as high compared to using a transmission profile where the expected wind power is subtracted from the transmission capacity.

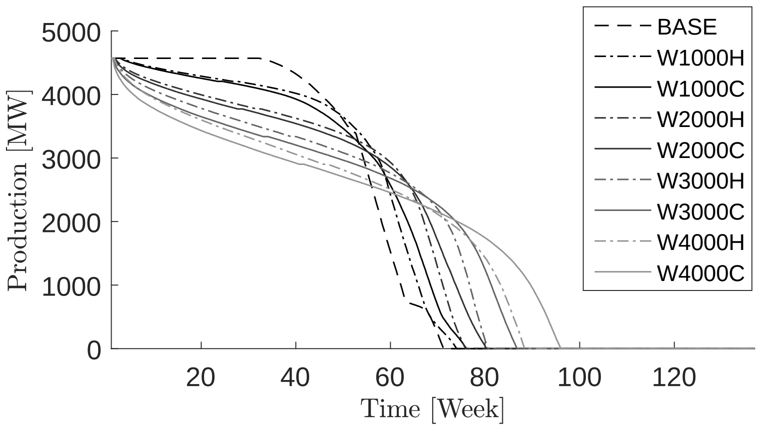

Figure E.4: Duration for storable hydro power production for the three year planning period.

The differences in the duration of the storable hydro power plant between coordinating or not also changes with the changing differences in the production pattern as shown in Figure E.4.

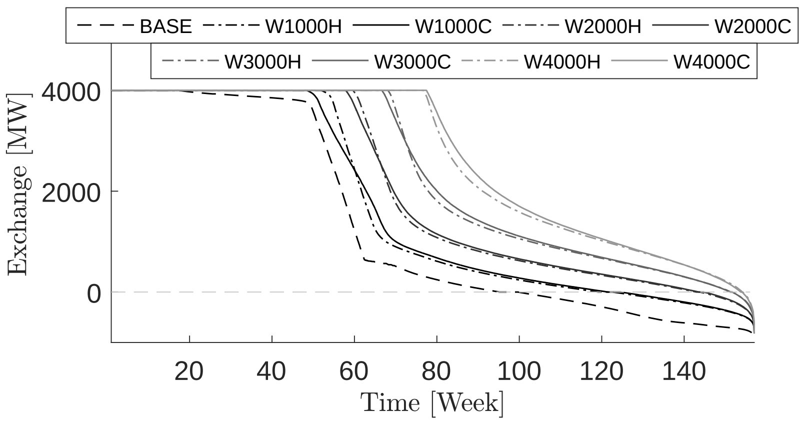

Figure E.5: Duration of exchange for the three year planning period.

Figure E.5 shows the duration of exchange on the transmission lines, more production in the late winter leads to more congestion when not coordinating and more transmission on high levels.

Table E.1: Comparison of total revenue pr. year.

	Wind Power [MW]	1000	2000	3000	4000
Hydro	Storable HP [bnNOK]	3.512	3.462	3.388	3.275
	End value water[bnNOK]	1.888	1.942	1.983	2.074
	RoR HP [bnNOK]	0.730	0.730	0.730	0.729
	Wind [bnNOK]	0.587	1.171	1.752	2.317
Coord	Storable HP [bnNOK]	3.515	3.451	3.371	3.235
	End value water [bnNOK]	1.829	1.887	1.913	1.953
	RoR HP [bnNOK]	0.731	0.731	0.731	0.731
	Wind [bnNOK]	0.587	1.175	1.763	2.352
Diff.	Storable HP [%]	0.08	-0.31	-0.50	-1.23
	End value water [%]	-0.031	-0.028	-0.035	-0.059
	RoR HP [%]	0.03	0.11	0.16	0.32
	Wind [%]	0.09	0.32	0.62	1.53

Table E.1 shows how revenue is moved from storable hydro power to RoR hydro and wind power where a larger shift in revenue is observed compared to using a transmission capacity profile.

Table E.2: Profit from power exchange for the planning period when using a constant transmission capacity.

Wind Power [MW]	1000	2000	3000	4000
Hydro [bnNOK]	10.964	12.448	13.983	15.446
Coord [bnNOK]	10.941	12.433	13.982	15.477
Diff [%]	-0.213	-0.126	-0.007	0.197

The profit from energy sales is shown in Table E.2 where a positive trend is observed as more wind power is included in the system. The positive trend is a result of the increasing congestion which is not considered when not coordinating in Table E.2. The same tank water cost is used for storable hydro as for RoR hydro and wind power in Table E.2 and considering the increased congestion in the strategy when not coordinating would result in a negative trend as shown in appendix D.

F Conference Article

This appendix contain a conference article submitted for the 51st International Universities Power Engineering Conference in Coimbra, Portugal

Coordination of Hydro and Wind Power in a Transmission Constrained Area using SDDP

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***Abstract*—In this work we use a production scheduling model based on Stochastic Dual Dynamic Programming (SDDP) to investigate the effects of coordinating hydro and wind power production in a transmission-constrained area. A case study is performed on an aggregated representation of a region in western Norway for a future situation with a significant integration of wind power. Two strategies for hydro reservoir utilization are developed using the SDDP model, one only considering hydro power and one considering both hydro and wind power. These two strategies are then tested in an out-of-sample simulator with equal conditions so they can be compared properly.**

Results from the case study show that coordination results in a lower reservoir level which reduces spillage and wind curtailment significantly. Coordination increases the export of energy out of the system by increasing the transmission on intermediate levels. Revenue is moved from storable hydro power to run-of-river hydro and wind power as coordination moves storable hydro power production to less profitable periods to reduce spillage and curtailment.

***Index Terms*—Hydroelectric power generation, Power system simulation, Wind energy integration.**

I. Introduction

As a part of the initiative to reduce the effects of climate change by moving towards an increased share of energy from renewable sources, the European Union has passed the Energy Directive which states clear targets for renewable energy development the next decades. As a part of the European Economic Area (EEA) Norway is affected by EU politics and has currently committed to increase the production of renewable energy by 13,2 TWh within 2020 [1]. The main tool to increase the production of renewable energy is the green-certificate market shared by Norway and Sweden which is expected to increase investments in hydro and wind power.

The number of wind farms in Norway is low compared to the available resources and as the cost of wind power production has dropped significantly the latest years [2] the interest in wind power has increased. Many wind farm projects have received permits from the authorities but most of these projects remain undeveloped due to low power prices and poor transmission capacity. Recently, the largest onshore wind power project in Europe was pronounced by the Norwegian central coast, summing up to 1000 MW of installed wind power capacity. Following this investment, a significant investment in the transmission grid is due. The grid surrounding these rural coastal areas is often quite weak and large investments in the transmission grid are necessary to be able to benefit from the good wind resources.

In [3] the problem of phasing in wind power in the Norwegian power system is studied for a case in Northern-Norway. The study shows that development of even moderate amounts of the available wind resources will cause a significant drop in the power price, significant transmission congestions, increased marginal transmission costs and increased amounts of spillage. The study concludes that development of transmission capacity should be internalised in the wind power projects and that such an internalization would make many projects in rural areas, with weak grid connections, less cost efficient such that other projects should be prioritized instead.

Currently the Norwegian power production portfolio consists of about 97 % hydro power with a total storage capacity of 84 TWh [4]. Wind power could be faster and more cheaply integrated by taking advantage of the characteristics of storable hydro power. Coordination of hydro and wind power may reduce the need for grid investments by adjusting the hydro power production to utilize the transmission lines more optimally. The advantages and disadvantages of such a coordination needs to be investigated further to assess the socio-economic benefits of such a solution.

Several papers have been published on coordination of hydro and wind power for short-term scheduling. In [5], [6] a short-term scheduling algorithm for coordination of hydro and wind power is developed for bidding in the spot market, the algorithm is applied in a case study and compared to hydro power scheduling without considering wind power. In these papers the hydro power plants and wind power farms are assumed owned by different utilities, hydro power is assumed to have priority on the transmission lines and wind power would be curtailed when the lines are congested. The main conclusions from these papers are that coordination between the hydro power utility and wind power utility is mutually beneficial, reduces wind energy curtailment and improves the utilization of the transmission lines.

In [7] the short-term scheduling algorithm from [5], [6] is expanded to include the regulating market. Furthermore [8] proposes a scheme for splitting the extra value caused by the coordination. All the previous papers focuses on short-term planning and uses fixed end-of-week reservoir volumes in the algorithms and thus purposely neglecting the possible long term effects of the coordination.

Coordination of hydro and wind power has previously also been studied for long- and medium-term scheduling. In [9] and [10] an algorithm for coordination of hydro and wind power is outlined which uses a predefined reservoir strategy for hydro power as input. Depending on which control-strategy is chosen, adjust hydro power production or curtail wind power, the original hydro power strategy is modified or used as is when the system operation is simulated. [10] includes a comprehensive case-study for a region of the power system in Northern-Norway, the study shows that coordination between hydro and wind power increases the amount of wind power that can be integrated into the system by increasing the utilization of the transmission lines and reducing the spillage. As both of the previously mentioned medium-term studies uses the same simulation method and gives positive results in regards to wind power integration it is interesting to see how these results holds up compared to a more formal optimization method.

A modern state-of-the-art method to solve long- and medium-term optimization problems is stochastic dual dynamic programming (SDDP), this method was introduced for power system applications in [11] and can be used for a wide range of problems. Some of the main advantages with the SDDP algorithm compared to more traditional methods as e.g. the water-value method, based on stochastic dynamic programming (SDP) [12][13], is that it allows for many state variables and more detailed modelling of the power system while keeping the problem tractable and capturing the dynamic effects between different reservoirs.

In [14], [15] a SDDP-model is developed and used for medium-term hydro power scheduling of multi-reservoir systems, combining SDDP and SDP with a Markov-chain for stochastic representation of the spot price. A similar model including a linear grid model is used in [16] to model a future case of the Icelandic power system with wind power, pumped-storage hydro power and a cable to the UK. [16] shows that using a fine time resolution and including an internal grid model with linearised power flow equations is important to obtain a realistic solution.

The main objective of this paper is to provide a basic analysis of the effects regarding coordination of hydro and wind power and thus a one-area model where the internal transmission grid is neglected and all the power plants in the area is aggregated into one storable hydro power plant, one run-of-river hydro power plant and one wind power farm serves as a sufficient model.

This paper is organized as follows; Section II gives a brief introduction to the most important features of the SDDP-algorithm, other basic modelling features are explained and the LP-formulation for the model is presented. A case study is outlined and results are presented in Section III. Finally, the main conclusions and suggestions for further work are given in Section IV.

II. METHOD AND MODELLING

A. LP-problem

The LP-problem for the power system in time-stage t is formulated in Equation (1) to (8) and consist of the objective function (1), reservoir balances (2), energy balance (3), discharge limits (4), reservoir capacity limits (5), import and export limit (6), (7) and cuts (8).

The objective function in (1) maximizes energy sales from the area under the assumption that the local load has to be covered, this is the same as optimizing the production and can be shown by substituting the energy balance (3) in to the objective function.

$$\hat{\alpha}_t(v_t, z_t) = \max\{\pi_t^S e_t^S - \pi_t^P e_t^P - \pi^R r_t - \sum_{i\in\mathcal{U}} \pi^T \varpi_{ti} + \hat{\alpha}_{t+1}\} \tag{1}$$

s.t.

$$v_{ti} + q_{ti} + s_{ti} - \varpi_{ti} = v_{(t-1)i} + I_{ti}(z_{(t-1)i}) \quad \forall i \in \mathcal{U} \tag{2}$$

$$\sum_{i\in\mathcal{U}} q_{ti} - e_t^S + e_t^P + r_t = D_t \tag{3}$$

$$0 \leq q_{ti} \leq Q_i^{max} \quad \forall i \in \mathcal{U} \tag{4}$$

$$0 \leq v_{ti} \leq V_i^{max} \quad \forall i \in \mathcal{U} \tag{5}$$

$$0 \leq e_t^S \leq T_t^{S,max} \tag{6}$$

$$0 \leq e_t^P \leq T_t^{P,max} \tag{7}$$

$$\hat{\alpha}_{t+1} \leq \alpha_{t+1}^* + \sum_{i\in\mathcal{U}} \pi_{(t+1)i}^j (v_{ti} - v_{ti}^*) + \sum_{i\in\mathcal{U}} \mu_{(t+1)i}^j (z_{ti} - z_{ti}^*) \quad \forall j \in \mathcal{H}_i \tag{8}$$

In the reservoir balance for a unit i discharge, q_{ti}, and spillage, s_{ti}, is treated as outgoing energy while inflow, $I_{ti}(z_{(t-1)i})$, and tank water, ϖ_{ti}, is ingoing energy. Tank water has to be included due to the VAR(1) model used for modelling the inflow. Negative inflow can occur when the seasonal inflow-profile is at its lowest, if the reservoir levels are low the problem might become infeasible due to a negative right-hand-side of the reservoir balance. Use of tank water is penalized(π^T) in the objective function as it doesn't represents a real system state.

In the energy balance curtailed load, r_t, discharge and purchased, e_t^P, energy is energy into the system while sold, e_t^S, and locally consumed, D_t, energy is energy out of the system. Load curtailment is penalized, π^R, by the value of lost load in the objective function as it has a high socio-economic cost and is very undesirable. There is a small price difference in the objective function between the price to sell, π_t^S, and purchase, π_t^P, energy to avoid selling and purchasing at the same time.

Transmission is represented by a constant maximum transmission capacity when calculating the strategy for coordination and in the simulator for both cases. When not coordinating, a transmission capacity profile is used in the strategy calculations to account for the reduced transmission capacity from the hydro power point-of-view due to wind power production. The transmission capacity profile is calculated by subtracting the expected wind power production from the transmission capacity limit.

B. Inflow modelling

The stochastic parameters in SDDP must be stage-wise independent, inflow and wind typically exhibit serial correlation which can be accounted for by state-space enlargement. Both wind and inflow have a seasonal pattern, this is first extracted by normalizing the series. The normalized series are modelled using a vector auto-regressive model of order one, VAR(1) [17]. The multivariate time series comprise reservoir inflow, run-of-river (RoR) inflow and wind. The VAR(1) model is formulated in Equation 9, where $\boldsymbol{\phi}$ is the auto-regressive coefficient matrix for the inflow and wind data and $\boldsymbol{\epsilon}_t$ is a random error.

$$\mathbf{z}_t = \boldsymbol{\phi}\mathbf{z}_{t-1} + \boldsymbol{\epsilon}_t \tag{9}$$

The expression for the inflow of inflow series j in time-stage t, I_{tj}, is shown in Equation 10. Where $\boldsymbol{\phi}_j$ is row j of the autoregressive coefficient matrix.

$$I_{tj}(\mathbf{z}_{t-1}) = \mathbf{z}_t\sigma_{tj} + \mu_{tj} = (\boldsymbol{\phi}_j\mathbf{z}_{t-1} + \epsilon_{tj})\sigma_{tj} + \mu_{tj} \tag{10}$$

As seen from Equation 10 the inflow in a given week, I_t, is dependent on the inflow in the previous week through the inflow state variables, $\mathbf{z}_{t-1}$, while the stochastic noise parameter, ϵ_t, is independent of previous weeks inflow. The noise distribution is discretizised into a number of branches using a fast forward scenario reduction algorithm described in [18].

C. Stochastic Dual Dynamic Programming

Hydro power scheduling and many other real-life applications are often significantly affected by uncertainty as future values of parameters are hard to predict e.g. spot price, inflow and wind speed. By using a discrete description of the state-variables the stochastic problem can be solved to optimality using Stochastic Dynamic Programming (SDP). A problem using SDP is that the problem grows exponentially with the number of state-variables. The exponential growth in problem size causes the solution-time to become too large for problems with detailed Mixed Integer Program (MIP) modelling.

Another way of solving a stochastic problem is by formulating it as a linear problem. Stochastic linear problems are usually decomposed by time-stage or scenario, when decomposing by time-stage a scenario-tree is created due to the discrete stochastic data. Solving a multi-stage stochastic linear problem to optimality involves solving all the nodes in the scenario-tree which grows exponentially with the number of time-stages. The exponential growth in problem size causes the solution-time to become too large for problems with a detailed time-resolution or a long time-horizon.

Stochastic Dual Dynamic Programming is a statistically based approximation method for reducing the solution time of the multi-stage stochastic problem. The scenario-tree is constructed using stage-wise independent data i.e. all realizations of the uncertain data has the same discrete probability distribution for all nodes within a time-stage. Constructing the scenario-tree by using stage-wise independent data enables Sample Average Approximation (SAA) to be used solving the problem by sampling different paths through the scenario-tree. According to the SAA-theorem the solution of the SDDP method converges towards the optimal solution as the number of samples increases.

A common formulation of the linear problems in multistage stochastic programs is derived using dual theory and Benders decomposition where cuts are created to provide an approximate description of the future profit function[19]. An advantage with SDDP is that the stage-wise independent property of the uncertain data allows cuts to be shared amongst all nodes within a time-stage and thus provide a better description of the future cost function.

The SDDP algorithm uses an iterative process with a forward and backward run, in the forward run the LP-problem is solved for all time-stages and solutions are obtained using the current cuts to describe the future value function. In the backward run the solution of the state variables obtained in the forward run is used to create more cuts which is added to the LP-problems to improve the description of the future value function [20]. A more comprehensive explanations of the SDDP-method are found in e.g. [19] or [20].

D. Initial Reservoir Level and End-Cuts

The strategy is calculated over a period of three years with equal demand and prices each year. As it is normal for the reservoirs to be emptied before the spring flood or flooding in the autumn for most of the cases the first and third year provides a decoupling from the values in each end of the planning period for the strategy in the second year. When studying long-term effects of coordination, the focus is on the second year as it is least affected by the initial reservoir level and end cuts while calculations on revenue is performed for the whole planning period.

E. Simulator

The strategies obtained from the strategy calculations are compared in an out-of-sample simulator, the simulator is similar to the forward run in the SDDP-algorithm for the coordination case but with pre-sampled inflow and wind series. In the simulator the inflow and wind series are pre-sampled using a continuous description of the noise distribution which provides better samples more similar to the underlying data.

To keep an acceptable calculation time the strategy calculations uses a lower number of discrete noise levels and data samples as the main driver of the calculation time is the backward runs where the cuts, i.e. the reservoir strategy, is calculated. The simulator uses a significantly higher number of inflow and wind samples compared to the strategy model which further helps providing a better representation of the possible system states in the scenario-tree.

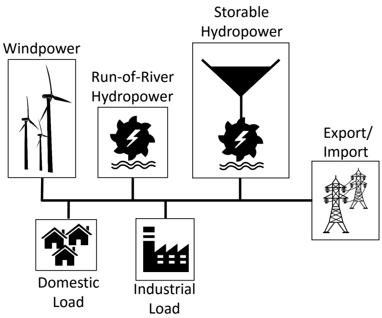

Fig. 1. Illustration of the power system model.

III. Case Study

A. System modelling

A one-area model is created to represent the grid-constrained area as illustrated in Figure 1, internal transmission-lines are neglected and power plants are aggregated. The power plants are aggregated based on the following categories, storable hydro power, run-of-river (RoR) hydro power and wind power. The local load is represented by a deterministic load series based on the average load, while the transmission-lines are modelled as restrictions on the amount of power that can be exchanged with the external power market. To focus on the stochastic properties of inflow and wind a deterministic power-price is used for power sales to, or purchases from, the external market.

To limit the scope of this analysis and due to the computing resources available a time-step of one week is chosen. The model in this paper is based on many of the same principals as in [14] and [15], but it is also significantly modified to fit to the area model. No considerations are taken with respect to different ownership of power plants or transmission-line priorities as in [5], [6] and [7].

B. Case system

Sogn og Fjordane is a region in western Norway with a lot of potential for development of small hydro power and wind power. It is the region in Norway with the best potential for development of small hydro power and according to the Norwegian Water Resources and Energy Directorate (NVE) the region has about 4.89 TWh of total remaining hydro power resources as of January 2015 [21].

It is also one of the regions in Norway with the best wind power resources according to a wind power resource analysis on behalf of NVE, while the regions in northern Norway are the best [22]. Currently there are only one wind farm in the region with a capacity of 23 MW and a approximate 59 GWh of yearly production, but a lot of permits are given for new projects. About 750 MW of new wind power projects are currently considered and most of them have a final permit.

It's difficult to predict how the system will develop in the future with good accuracy but by using data from [23] and [24] an approximate description of the production portfolio for 2030 can be formulated. Table I includes the estimated power system production capacity and energy for 2011, 2014 and moderate and high predictions for 2030 [23], [24]. The moderate and high prognoses in [24] equals developing about 68% and 92% of the remaining hydro power resources and in Table II these predictions are broken down in categories based on data from [23].

TABLE I
Total Power and Energy for the power system.

	2011	2014	2030-Mod	2030-High
Power [MW]	3 743	4 139	5 500	5 900
Energy [GWh]	12 601	13 900	17 500	18 750

TABLE II
Prognosis for the power system in 2030.

	Storable Hydro Power		RoR Hydro Power	
	Mod	High	Mod	High
Power[MW]	4 360	4 570	1 140	1 330
Energy[GWh]	13 700	14 320	3 800	4 430
Future Power Share	0.57	0.56	0.43	0.44
Future Energy Share	0.50	0.50	0.50	0.50
Power Increase	30%	36%	199%	249%
Energy Increase	22%	27%	181%	227%

By assuming a future degree of regulation (Reservoir Capacity/Yearly Inflow) at 0.71, same as in 2011[23], the aggregated reservoir capacity is estimated to be 9 730 GWh and 10 170 GWh for the moderate and high case respectively.

Future local load is expected to range between 7000 GWh and 9000 GWh dependent on development of the Energy Intensive Industry [24], a conservative local load estimate at 7000 GWh is used in this analysis. A large transmission capacity at 4000 MW used in this analysis as it provides almost no constraint to the system in the base case with no wind power.

Inflow, wind and demand records for the case study are provided by SINTEF Energy Research and adjusted to fit the energy quantities in the specified cases. Wind records used in this paper are energy records obtained from re-analysis data which is adjusted for regional effects [25]. The inflow and wind energy profiles are shown in Figure 2 for the high 2030 case with 1000 MW installed wind power capacity.

The inflow profiles for storable and RoR hydro power differ significantly from each other as most of the hydro power reservoirs are located at a higher altitude than the RoR hydro power. Due to the high altitude the inflow in the winter is small as most of the precipitation is snow, a significant peak in the inflow-profile occurs as the snow stored throughout the winter melts in the spring.

C. Results

- Hydro (H): Optimization of hydro power production.
- Coord (C): Coordination of hydro and wind power production.

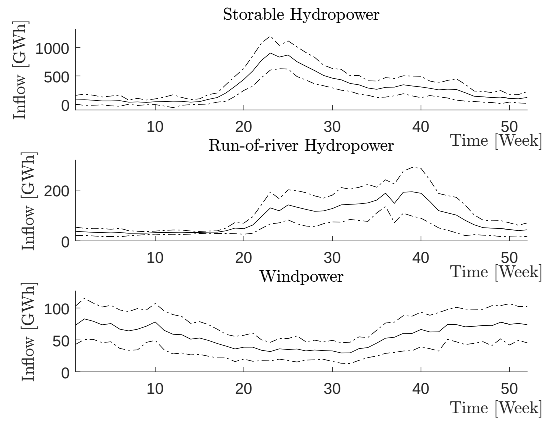

Fig. 2. Aggregated inflow and wind profiles for Sogn og Fjordane, with mean and standard deviations.

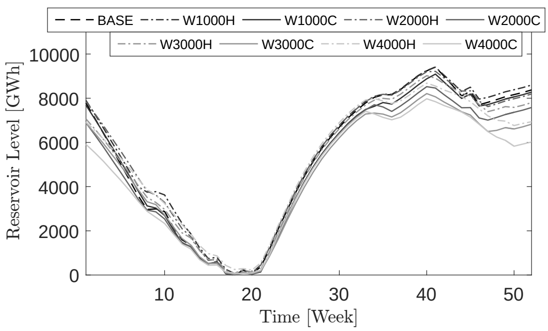

Fig. 3. Reservoir level for storable hydro power.

As shown in Figure 3 the reservoir level is reduced in the winter as more wind power is included regardless of coordination or not. Coordination results in significantly larger reductions in the reservoir level as the amount of wind power increases. A lower reservoir level during the winter allows the storable hydro power to adjust the production dependent on the highly intermittent wind power without risking additional spillage.

Increasing the amounts of wind power in the system decreases the number of hours of storable hydro power generation at high power levels regardless of coordination or not as shown in Figure 4. Coordination results in a small shift in production from high to lower levels and an increase in total production for storable hydro power as the spillage is reduced. The shift in duration is a result of the reduced reservoir level as production is moved to periods with higher RoR hydro power inflow.

Curtailment of RoR hydro power and wind power is a result of spillage from the reservoirs as the marginal cost of

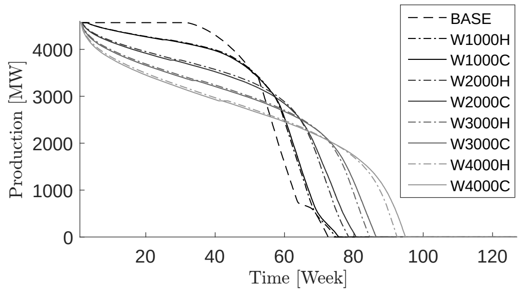

Fig. 4. Duration of storable hydro power production.

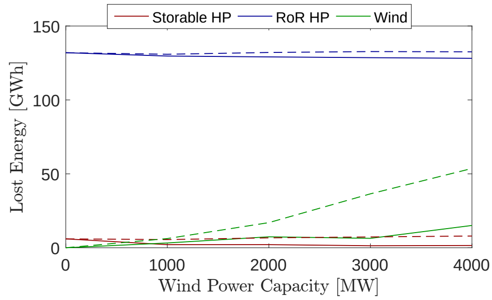

Fig. 5. Lost energy for different level of wind power integration. Hydro (dashed lines) and Coord (solid lines).

generation for storable hydro power also is zero when water spills and the inflow can't be stored for future production. Figure 5 shows how coordination, as a result of the reduced reservoir levels, significantly reduces the amount of wind power curtailment and spillage. The increased production results in a small increase in export on intermediate power levels. This shows how coordination takes advantage of the flexibility of a system with significant amounts of storable hydro power to allow large amounts of wind power to be integrated without increasing the amount of lost energy.

Table III shows how the revenue from storable hydro power is reduced for both strategies as more wind power is included in the system. More wind power results in more congestion during the autumn and winter when the prices are high and storable hydro power has to move some production to other periods with lower prices. Differences, defined as percentage difference from Hydro to Coord, shows how coordination shifts revenue from storable hydro power to RoR hydro and wind power as more storable hydro power production is moved to less profitable periods to reduce the reservoir level and energy loss.

As seen from the system profit in Table IV the increase in revenue from RoR hydro and wind power does not completely compensate for the lost revenue from storable hydro power. This is not as expected as previous studies on coordination shows an increased total revenue and might be a result of the

TABLE III
COMPARISON OF TOTAL REVENUE FOR THE PLANNING PERIOD.

	Wind Power [MW]	1000	2000	3000	4000
Hydro	Storable HP [bnNOK]	9.953	9.840	9.666	9.484
	End value water[bnNOK]	1.892	1.904	1.956	1.977
	RoR HP [bnNOK]	2.190	2.190	2.190	2.190
	Wind [bnNOK]	1.763	3.524	5.279	7.033
Coord	Storable HP [bnNOK]	9.967	9.813	9.650	9.450
	End value water [bnNOK]	1.862	1.892	1.930	1.954
	RoR HP [bnNOK]	2.190	2.191	2.191	2.191
	Wind [bnNOK]	1.764	3.527	5.288	7.048
Diff.	Storable HP [%]	0.14	-0.28	-0.17	-0.35
	End value water [%]	-1.58	-0.61	-1.32	-1.18
	RoR HP [%]	0.03	0.04	0.05	0.04
	Wind [%]	0.08	0.10	0.18	0.21

TABLE IV
PROFIT FROM POWER EXCHANGE FOR THE PLANNING PERIOD.

Wind Power [MW]	1000	2000	3000	4000
Hydro [bnNOK]	11.754	13.415	15.049	16.643
Coord [bnNOK]	11.740	13.381	15.018	16.602
Diff [%]	-0.116	-0.258	-0.209	-0.249

inflow model where some tank usage is forced as the reservoir capacity of the RoR hydro and wind power plants are zero. The differences in total profit are small and shows no clear trend as the amount of wind power increases.

IV. CONCLUSION AND FURTHER WORK

Coordination of hydro and wind power results in a lower reservoir level due to the uncertainty associated with wind power. A lower reservoir level contributes to keep the wind power curtailment low as the amounts of wind power in the system increases.

Coordination contributes to shifting storable hydro power production towards lower power levels as production is moved to periods with higher RoR hydro power inflow. The increased production results in a small increase of transmission on intermediate levels.

Revenue is shifted from storable hydro power to RoR hydro power and wind power when coordinating. A small negative result is observed in terms of total system profit but shows no clear trend as more wind power is included.

A. Further Work

Suggestions for further work is:

- Analysis with a more detailed model including internal transmission constraints and a more detailed description of the generation in the area, as in [16].
- Introduce price uncertainty by using a model where price is represented by a Markov-chain and the cut generation in the SDDP-algorithm is supplemented with SDP.

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