Measuring the Impact of Environmental Constraints on Hydropower Flexibility

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***Abstract*—Implementation of EU's Water Framework directive, meant to ensure sustainability of the hydropower production, may lead to new environmental constraints on hydropower systems. This can result in loss of production, reduced operational flexibility and consequently reduced income from production. Flexibility is here defined as the ability to adapt production to variations in power prices, whereas the production income is strongly influenced by the price level and sum production. This paper presents and evaluates two different measures that are used to quantify how new constraints affect system flexibility in the Norway and Sweden. These measures are the established Flexibility Factor, comparing achieved price with average price, and an imaginary equivalent electrical storage unit, which is parametrized by the equivalent storage and power capacity needed to compensate for the lost flexibility. The calculation and evaluation of the two measures are exemplified using two Norwegian water courses.**

***Index Terms* -- Hydropower Scheduling, Environmental Constraints, Flexibility of Supply, Energy policy.**

I. INTRODUCTION

As the share of variable renewable energy sources (VRES) increases, existing hydropower facilities will be more important as storage and flexibility providers [1]. In symphony with the ongoing power market changes, the physical and environmental requirements associated with hydropower operation are changing, e.g., through proposed revisions of hydropower concessions and the implementation of the EU Water Framework Directive. The directive strives to ensure sustainable use of water resources, balancing the multiple uses such as hydropower, irrigation, water supply, flood control and recreation [2]. Consequently, hydropower producers need to both adjust their operational schedules according to the new price patterns seen in the market and at the same time relate to new operational constraints. These constraints will impact the flexibility of operating the hydropower system, probably leading to a loss of production and/or revenue for the producer [3].

Because flexibility is assumed to be increasingly important for future system operation it is valuable to have simple and easily understandable measures for flexibility that can be used to compare and communicate the consequences of new environmental constraints. We loosely define flexibility of a hydropower system as the ability to adjust its production according to a price signal. Put in another way, it allows for production when there is a high demand. It follows that some production systems naturally have a higher flexibility than others, and that the flexibility depends on the system's storage and discharge capabilities. When constraints act on a hydropower system, the feasible production area is reduced, and the resulting optimal production will be less than or equal to the unconstrained case. To find out whether the flexibility, as defined above, is also reduced, measures for flexibility or flexibility change must be used.

In this work we take the perspective of a price-taking hydropower producer with the objective to maximize expected profit over a defined planning period. The producer's operation is typically planned by use of medium-term hydropower scheduling models, providing time series of hydropower production according to defined price input [4].

Traditionally, the expected loss of energy production has been an important measure of the impact of environmental constraints. However, it does not measure the change in flexibility. A popular measure for flexibility is the so-called Flexibility Factor (FF) (in Norwegian: *verdifaktor* or *fleksibilitetsfaktor*), which shows the relationship between the producer's achieved price and the average price [5], [6]. The FF is a scalar number that is easy to understand and compare across systems. While the accumulation of all aspects of flexibility in one single number is easy to communicate, we find that the FF measure does not always lead to intuitive interpretations. Thus, it should be supported by other measures.

In this paper, a method complementary to FF for estimating the flexibility loss due to new environmental constraints in hydropower systems is presented and assessed. The method was first presented in [7], and conceptualizes the

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flexibility loss as an imaginary Equivalent Electrical Storage (EES). The EES can be visualized as a battery with defined storage and charge/discharge capacities suited to replace the lost flexibility. The FF and EES measures are estimated for two different hydropower systems in Norway with different types of environmental constraints. Based on these case studies, advantages and drawbacks are evaluated for the two metrics.

II. METHOD

We investigate hydropower systems for which one can define a *reference* case and a *constrained* case where additional environmental constraints have been introduced. The optimal operation of producers' hydropower portfolio for each case is found by a medium-term hydropower scheduling model, assuming a risk-neutral and price-taking hydropower producer. Model results, in terms of time series of generation schedules on portfolio basis, are used to assess the flexibility loss.

A. *Flexibility Factor – FF*

The FF provides an estimate of the flexibility of a hydropower system for a specific case, as it relates the achieved price with the average price. The FF is defined as the relationship between the average achieved price π^* and the average price $\overline{\pi}$:

$$FF = \frac{\pi^*}{\overline{\pi}} = \frac{I/p}{\overline{\pi}} \tag{1}$$

The average achieved price is the relationship between the total revenue I and the total produced hydropower p in GWh. The FF could potentially also be adjusted for overflow.

B. *Equivalent Electrical Storage – EES*

The EES represents the loss of flexibility in the constrained case as an imaginary flexible energy storage. In other words, we define a storage unit needed to compensate for the flexibility loss in the system over a specified time period caused by the constraint. This EES is parametrized by a storage capacity [GWh] and a power capacity [MW], see Fig. 1.

We subtract the average loss of production to emphasize on the flexibility loss, separate from the loss of income. What is left is the energy that is moved in time from an optimal to a suboptimal production allocation.

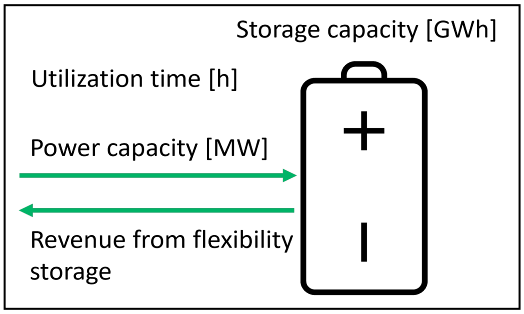

Figure 1: Illustration of the EES parameters

The energy storage capacity E of the EES must be large enough to provide the same flexibility that was lost due to the introduced constraint. It can be calculated as the difference between the maximum and the minimum values of the balancing energy B, which is the accumulated production difference due to the introduced constraint, reduced with the total production difference for the time period:

$$E = B^{\max} - B^{\min}$$
$$B_t = \Sigma_{\tau=1}^{t} \Delta p_\tau - \Sigma_{\tau=1}^{t} \overline{\Delta p} \tag{2}$$

Here Δp_t is the difference in production in GWh between the reference and constrained cases for time step t and $\overline{\Delta p}$ is the average production difference per time step in GWh, introduced by the constraint. The deduction of the energy storage capacity is illustrated in Fig. 5. The power capacity P of the EES is an equivalent power capacity large enough to compensate for the reduced exploitation of the available power production capacity in the constrained case. As a trade-off between flexibility and costs of the EES power, and to make the measure more robust towards extreme cases, it is defined as the 95-percentile of the absolute value of the difference in produced power, due to the introduction of the constraints. Furthermore, the average loss is subtracted from the production difference in each time step:

$$P = 95\%\left(\left|\Delta p_t\right| - \left|\overline{\Delta p}\right|, \forall t \in (0,T)\right) \tag{3}$$

The deduction of the power capacity of the EES is illustrated in Fig. 7. The revenue I from the flexibility storage equals the lost income of the system due to the constraint, reduced with average income loss. It can be illustrated as the cost of charging the EES minus the gain from selling power from the storage and has a positive sign if there is a loss of flexibility due to the constraint. The revenue can be found by multiplying the price of each time step π_t with the balancing energy B:

$$\begin{aligned} I &= \left(\sum_{t=0}^{T} \Delta p_t - \sum_{t=0}^{T} \overline{\Delta p}\right)\pi_t \\ &= \sum_{t=0}^{T} (\Delta p_t - \overline{\Delta p})\pi_t \end{aligned} \tag{4}$$

The utilization time is the relationship between the storage capacity E and the power capacity P.

III. CASE STUDIES

The FF and EES metrics described in Section II were tested in a set of case studies using the medium-term hydropower scheduling model ProdRisk [8]. ProdRisk is based on stochastic optimization and assumes a risk-neutral price-taking producer optimizing the use of water resources while accounting for uncertainty in future market prices and inflows. The constrained scenarios are implemented with additional constraints in the optimization problems.

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The case studies in this paper consider the introduction of environmental constraints in two hydropower systems: Sokna in Central Norway and Aura in Western Norway. Schematic illustrations of both systems are shown in Fig. 2. The total system storage capacity of Aura and Sokna are 1413 GWh and 151.2 GWh, respectively, whereas the total system production capacity of Aura and Sokna are 310 MW and 57.9 MW, respectively. The utilization times for Aura and Sokna are 4558 hours and 2611 hours, respectively.

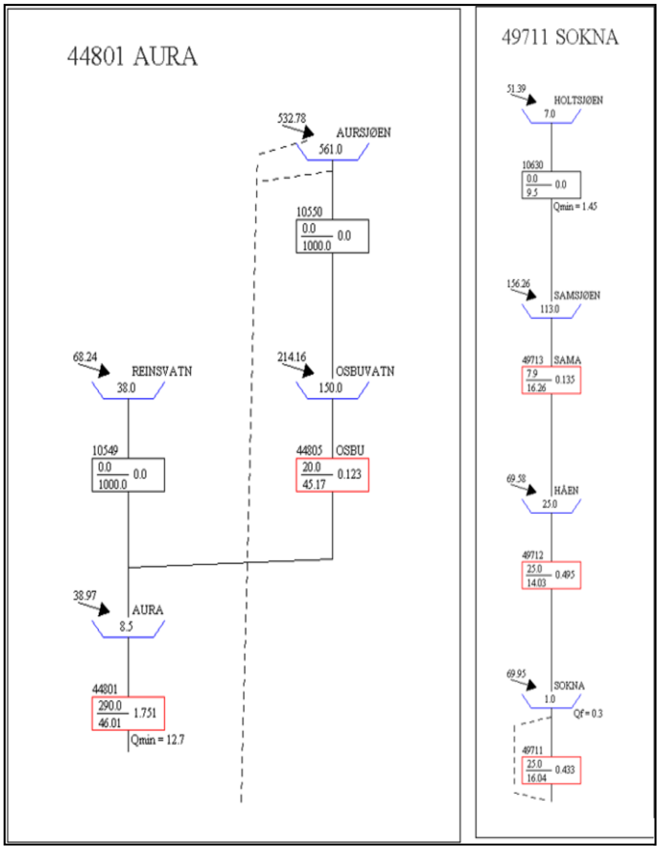

Figure 2: Schematic illustration of the Aura (left) and Sokna (right) hydropower production systems.

TABLE I. EVALUATED CASES

Case #	**System**	**Description**
1	Aura	Reference case
2	Aura	Soft min. reservoir constraint for Aursjøen
3	Aura	Absolute min. reservoir constraint for Aursjøen
4	Sokna	Reference case
5	Sokna	Soft min. reservoir constraint for Samsjøen
6	Sokna	Absolute min. reservoir constraint for Samsjøen

We consider both a *soft* and an *absolute* minimum reservoir constraint on Aursjøen and Samsjøen, which are the largest reservoirs in the Aura and Sokna systems, respectively. The soft constraint does not allow discharging water (through the power station) when the reservoir volume is below the limit of 85%, while the absolute constraint prevents the reservoir volume to move below 85%. For Samsjøen, the constraint is active from week 18 to week 35, with no reservoir constraint outside of this period. The two systems have additional environmental constraints as described below and kept constant across cases. The Sokna system has time-dependent constraints on minimum reservoir and minimum discharge for Holtsjøen, as well as the minimum bypass for Sokna. The Aura system has a constant minimum discharge constraint for the Aura reservoir.

The FF is evaluated for each of the cases in Table I, whereas the EES parameters are computed for the constrained cases 2, 3, 5 and 6 in relation to their respective reference cases 1 and 4.

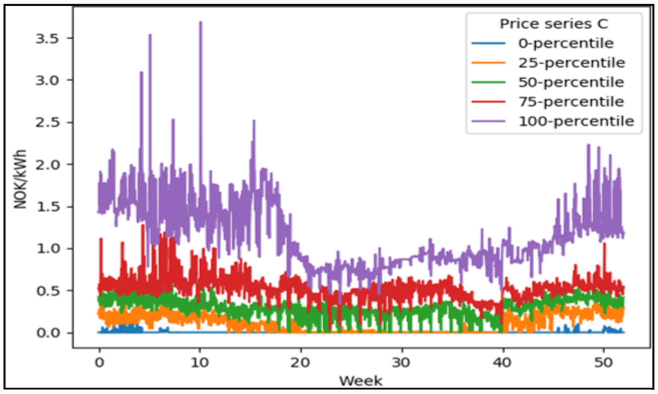

Figure 3: Price series used in the evaluation: All price scenarios are represented as percentiles.

For these case studies, ProdRisk uses a time resolution of 3 hours and an optimization horizon of 5 years. A total of 30 historical inflow scenarios are combined with a set of price scenarios to provide exogenously defined stochastic variables. The percentile wise distribution of the weekly prices is shown in Fig. 3.

IV. RESULTS

Fig. 4 shows the production for 30 consecutive scenarios with 3 hours' time resolution, sorted by price and then averaged over 4 weeks for visibility purposes, for the cases 1 and 3. The blue bars are production for the reference case, whereas red bars are production for case 3. The purple fields on the bars are the production volumes that coincide for both cases. The price is shown as a blue line, decreasing from left to right. The figure shows that the flexibility to produce at high prices is significantly limited in the Aura system when introducing an absolute minimum reservoir constraint in Aursjøen in case 3. As shown later in Table III, the FF is reduced by approximately 10% in case 3 compared to case 1.

To further assess the loss of flexibility, the EES parameters are calculated for the comparison between the reference case and the constrained cases. The deduction of the storage capacity is illustrated in Fig. 5, where the balancing energy B and storage capacity E were found using (2). The EES storage capacity E for case 3 is calculated to be 967.2 GWh, which is about 68% of the total storage capacity for the reference case. This large number is a result of the chosen 30-year time frame where the calculated EES is the difference

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between the highest and lowest value during the whole period. A storage capacity calculated per year could be a more useful measure and give some information on the lost seasonal storage. Note that the total energy loss, found to be 4300.83 GWh in Fig. 5, is not included in the EES, as this is subtracted in (4) as a constant loss of production during the whole simulation period.

The balancing energy *B* for all scenarios for case 3 are shown in Fig. 6. Differently from the balancing energy shown in Fig. 5, the balancing energy found per scenario in Fig. 6 clearly shows how a negative balance accumulates prior to the absolute minimum reservoir constraint and is reverted afterwards. A major task of the EES would therefore be to provide flexibility on a seasonal scale. This way of calculating *E* and *I* gives significantly lower dimensions of the EES parameters, as the storage covers flexibility loss for one year only.

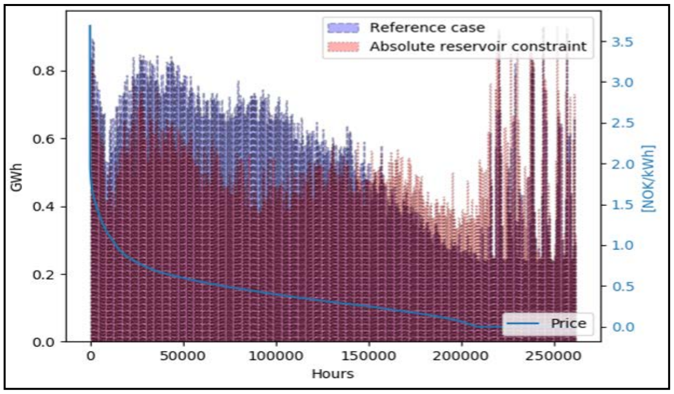

Figure 4: Production in the Aura system averaged over 4 weeks, sorted according to decreasing price for cases 1 and 3 for 30 consecutive scenarios.

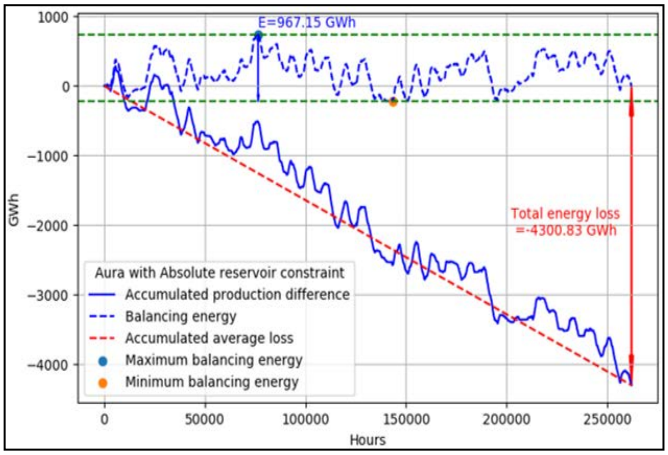

Figure 5: Illustration of the deduction of the EES storage capacity for case 3 compared to case 1 for 30 consecutive scenarios.

EES capacity is shown in Fig. 7, where the capacity *P* can be calculated using (3). As in the optimization, the computation of *P* use a time resolution of 3 hours. In [7] the data was down sampled to 12-hour time steps in the calculation of *P* for the measure to reflect the loss of flexibility on the diurnal time scale. The revenue *I* for the flexibility storage accumulates a sum over the simulation scenarios. Therefore, this parameter must be divided on the number of simulated scenarios to be comparable to the total system income. An alternative approach is to calculate *B* and *I* for each scenario, and then find their 95-percentiles.

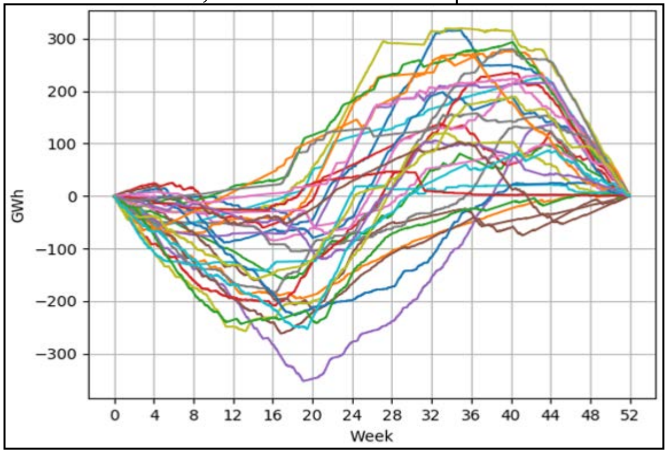

Figure 6: Balancing energy between case 3 and case 1 for parallelized scenarios

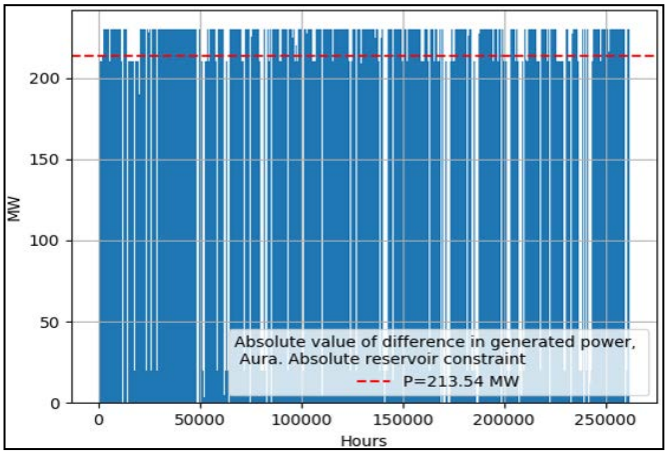

Figure 7: Illustration of the deduction of EES production capacity for case 3.

The expected outcome for the EES parameters and the FF would be an increasing flexibility loss due to the severity of the restriction, compared to the reference case. The computed EES parameters in Table II and FFs in Table III mainly follow this hypothesis but have a few exceptions worth further investigation for the Aura system. We expected the FF to decrease with a more constrained system, as we observed for the Sokna system. However, the FF is increasing slightly from case 1 to 2, indicating increased flexibility in the Aura system when introducing the soft reservoir constraint. Most probably, some less favorable production is lost due to the constraint. The objective function is to maximize income – not price per production. Moreover, we find that the EES power capacity becomes higher for the soft-constrained case 2 than the absolute-constrained case 3. The columns for the relation between the EES and the total system capacity use the average yearly system income without compensating for overflow and variations in start and end reservoir volume, as the EES parameters do not compensate for these.

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Relating the two flexibility metrics FF and EES to each other, the increased FF for Aura from the reference case to the case with a soft reservoir constraint suggests a negative net income for the EES caused by the same constraint. This is not the case – the lost flexibility caused by the soft reservoir constraint indicates a yearly income reduction due to loss of flexibility of 21.62 MNOK, or 3.1% of the average yearly income, as shown in Table II. The simulated average net incomes for case 1 and 2 are 706.0 MNOK and 671.3 MNOK, respectively. The remaining income loss is due to production loss, not lost flexibility.

TABLE II. EES PARAMETER RESULTS FROM SOKNA AND AURA, AND RELATIONSHHIP BETWEEN EES AND THE TOTAL PRODUCTION SYSTEM

AURA	**85% soft reservoir constraint**	**EES/Total system capacity**	**85% absolute reservoir constraint**	**EES/Total system capacity**
Storage capacity [GWh]	469.7	0.332	967.2	0.684
Power capacity [MW]	226.0	0.729	213.5	0.689
Yearly revenue [MNOK]	21.6	0.031	90.3	0.128
Utilization time	2078.9	0.456	4529.1	0.994
SOKNA				
Storage capacity [GWh]	71.4	0.472	134.0	0.886
Power capacity [MW]	25.7	0.443	41.7	0.720
Yearly revenue [MNOK]	0.5	0.004	6.3	0.046
Utilization time	2781.8	1.065	2951.3	1.130

TABLE III. FF COMPUTATIONS FOR ALL CASES. THE AVERAGE PRICE FOR ALL CASES IS 0.359 NOK/KWH. THE TOTAL PRODUCED POWER AND INCOME ARE AVERAGED OVER ALL SIMULATED SCENARIOS.

Case	**Produced power [GWh]**	**Income [MNOK]**	**FF**
1	1661.0	702.2	1.178
2	1581.4	671.3	1.183
3	1486.1	568.4	1.065
4	318.9	136.2	1.189
5	318.3	135.5	1.185
6	310.7	127.0	1.138

V. CONCLUDING REMARKS

The objective of this research was to evaluate the flexibility metrics FF and EES through case studies on Norwegian hydropower systems. While FF is a separate estimate per case, EES describes a flexibility loss (or gain) compared to a base case. We conclude that both measures are useful when assessing the impact of environmental constraints, as they provide complementary information. However, further investigations are needed before concluding on the robustness and generality of the proposed EES metric. It is not straightforward to define the horizon which the EES should cover and the time resolution it should operate with. Thus, we suggest that questions related to the EES horizon and granularity are further investigated considering different types of constraints.

The FF metric is straightforward to compute and leads to an unambiguous conclusion about change in flexibility. It naturally captures both short- and long-term flexibility. However, it is strongly dependent on the magnitude of price variations and does not provide information about why and at what time-scale flexibility changes. The EES indicates how a flexibility loss over a defined period could be compensated for with the introduction of fictitious storage, defined by a storage volume and capacity. We find the visual approach for defining EES parameters insightful, identifying the time-scales at which flexibility is needed.

Counterintuitively, we found that the accumulated balancing energy from Fig. 5 could be negative, providing a net yearly flexibility income introduced by the environmental constraint and thus an increased flexibility. In Table II, this would appear as negative numbers, which could still be combined with a positive storage capacity of the equivalent storage.

Future work may involve evaluation of different types of constraints, analyzes of why constraints can cause negative accumulated balancing energies, and further elaborations on the time scales at which flexibility is measured by the EES metric.

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