Modelling of Environmental Constraints for Hydropower Optimization Problems – a Review

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***Abstract*—Hydropower plants and reservoirs can have negative impacts on their surrounding ecosystems. To limit such impacts, environmental regulations may be imposed. This paper provides a review of literature on the most commonly used environmental constrains in scheduling of hydro-dominated systems and proposed constraints for future market conditions. Furthermore, we review literature on how environmental constraints are included in hydropower scheduling methods and discuss the main modelling challenges. We find an increasing interest in modelling of environmental constraints in recent literature, and conclude by highlighting challenges to improving the representation of environmental regulations in hydropower scheduling models.**

I. Introduction

The European power system is going through rapid changes as a consequence of technological developments and political targets to limit climate change. Among the changes are integration of large capacities of variable renewable energy generation into the power system, increased cross-border transmission capacity and the decommissioning of traditional power generation technologies in several countries. The ongoing changes in the European power system are expected to give increased short-term variability in power generation and increase the need for balancing resources. Technologies that can respond to rapid fluctuations in intermittent renewable generation and load, such as hydropower, can play an important role as flexibility providers to the system [1]. Reservoir hydropower plant operators can adapt their operational profiles to the needs of the system by rapidly adjusting production. This flexibility benefits system operation and provides added value for hydropower plant operators in liberalized markets [2].

On the other hand, hydropower modify the surrounding ecosystems [3]. Hydropower projects may alter the flow regime downstream the hydropower outlet, leave bypassed river sections dry in longer periods, create barriers for fish migration due to the establishment of dams and impose impacts to the terrestrial ecosystem [4]. Flow alterations and associated ecological consequences are major environmental concerns which have been assessed in several studies. An evaluation of streams and rivers in the US found that 86% of the assessed cases had modified flow magnitude because of hydropower or other water use [5], while [6] found that 92% of in total 165 reviewed papers reported lower values for recorded ecological metrics as a result of flow alteration. The flow regime is central to sustaining the ecological state of rivers and can influence important factors such as water quality, nutrition, physical habitat and biotic interactions [7].

To limit the burden of hydropower on the local fluvial ecosystems, many countries impose regulations on the operation of hydropower plants. In the hydropower scheduling such regulations are normally represented as constraints on operations. In addition to an environmental benefit, environmental regulations normally also have an economic impact on the operation of the power system and the specific hydropower plant. The economic impact depends on the definition of the imposed constraint, the characteristics of the power plant and the system and market which the plant operate in. Accurate modelling of environmental regulation in the scheduling problem is therefore important to correctly assess the reduced flexibility associated with such constraints.

This paper provides a review of literature on current and future environmental constraints (ECs) in the scheduling of hydro-dominated systems from an environmental and modelling perspective. ECs are here defined as legislative conditions on operation of hydropower plants with the origin from ecological or social considerations. In section II we present the development of environmental regulations, the most commonly used mitigation measures and expected developments considering future market conditions. In section III, the representation of environmental regulations as operational constraints in the planning of hydropower and modelling challenges are discussed. Finally, we discuss the findings in section IV and highlight challenges to improve the representation of environmental regulations in hydropower scheduling models.

II. Environmental Regulations on Hydropower

In most parts of the world, the rights to operate hydropower plants are regulated through some form of licensing process controlled at different governmental levels [8], [9], [10], [11]. The level of environmental regulation and how it is controlled vary depending on how the power sector is regulated (e.g. centrally coordinated or deregulated market), the national or regional water resource management [12] and the priority of environmental considerations in general. We here discuss

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regulation framework and mitigation measures mostly based on the Nordic region and the US. However, there are clear similarities to how hydropower is managed in other European countries and Canada.

In some parts of the world, such as Europe and the US, hydropower is normally regulated through the licensing terms of the plant, where environmental regulations might be defined. However, many hydropower plants have licences that were granted up to a century ago that are currently under revision or will be revised [9], [13], [14], [10]. More than 400 licences can come up for revision only in Norway before 2022 [15]. In these processes, many plants can be imposed environmental regulation and measures to improve ecological conditions. It has been widely recognized that modifications of flow regimes is associated with ecological change and can have cascading impacts on the fluvial ecosystems [5], [6]. When revising environmental regulation of regulated water courses, environmental or societal gains have to be weighed against loss in hydropower production and security of electricity supply and at the same time fulfil environmental policy and regulations. Knowledge about the operational regime of hydropower plants is an important factor for understanding ecological responses to dam regulation and support development of mitigation measures for today and future market conditions [16].

The future of hydropower is closely linked to sustainable energy policies, as well as electricity market design and dynamics [1]. It is argued that the ongoing development of wind power in the Nordic region may give more frequent and rapid fluctuations in the operation of hydropower (hydropeaking) as a result of increase in balancing services provided from hydropower [17]. Such operations can have large additional environmental impacts downstream the outlet of the power plants compared to rivers exposed to traditional, base-load production [17]. Examination of data from 150 sites in Nordic rivers have shown that hydropeaking occur at a considerably high level, with an increasing trend over the last decade [18]. On the another hand, the magnitude of the hydropeaking operations in Norwegian rivers has been found to be moderate compared to selected rivers in Austria, Switzerland and Canada [17].

A. *Mitigation Measures Today and in the Future System*

There was a rapid progress in the 1970's in Europe and the US regarding the implementation of mitigation measures, such as minimum flow. This was a result of new environmental and freshwater legislation coupled with the needs of quantitative assessment of flows to protect aquatic species impacted by dam construction [19]. For example, in Norway before the 70's, all water was diverted from the bypassed rivers to the hydropower plant and no minimum flow requirements were defined in the majority of the licences. As the environmental movement was advancing the introduction of minimum flows was standardised as a small constant flow, sometimes diversified as seasonal flows [20]. From the late 1980's, we see cases where the environmental terms develop towards more dynamic release to better meet the ecological needs, e.g. including low flows, seasonal variations and artificial flood releases [21]. Environmental flows, also referred to as ecological flows and e-flows, have a firm place in many intergovernmental agreements and are integrated into water policy and legislation in several countries and regions around the world [19], such as the implementation the Water Framework Directive (WFD) [22] in Europe.

Traditionally, ECs focus on preserving certain flow or reservoir levels, or avoiding too rapid changes in water levels in rivers and reservoirs. It naturally follows that minimum flows and maximum ramping rates are commonly applied environmental regulations on operation of hydropower plants [23]. A table of representative environmental requirements issued in the US is provided in [10]. The list includes familiar requirements that impact operation, such as minimum release constraints (discharge or bypass) and constraints on ramping rates for flow and reservoir, as well as more extreme measures such as mandatory run-of-river operation. The lack of consistent data and strong local variations have made it difficult to develop quantitative guidelines to support regional environmental flow standards [6]. Hence, local assessments are necessary to evaluate to what extent environmental regulations can mitigate local environmental impacts [24].

When considering mitigation measures for hydropower operations under future system conditions, market optimisation and simulations of hydropower operations are recommended [25]. It has been demonstrated that environmental considerations can be united with power production [26]. The impacts on environmental conditions in reservoirs induced by hydropower under future market conditions have been analysed in [27], and it has been demonstrated that increasing supply of flexibility services from hydropower can result in more frequent and rapid hydropower induced water-fluctuations in the future [28]. Such types of operational regimes might not have been considered in the original licensing process, and the revision of licences are expected to give more advanced and sophisticated restriction to improve or sustain ecological qualities [15]. The terms in the revised licences may be more dynamic, based on the needs of the ecosystem and the hydrological state of the basin, e.g. environmental flow releases defined for finer temporal resolution [1] [29], [30] or flow regimes based on expected inflow [31].

B. *External Impacts of Environmental Regulations*

In addition to the intended ecological benefits, ECs often have other consequences, depending on the system where the plant operate and the formulation of the constraint. Normally, these are economic consequences, but can also be impacts on greenhouse gas emissions from the power system or other water use. ECs should ideally be determined based on marginal value. To estimate the marginal value, environmental and other contextual impacts are considered. It can be more challenging to quantify the environmental benefits than the economic costs of mitigation measures [32], but for some cases the benefits

[1] for example hour to hour or day to day basis rather than seasonal

of environmental mitigation measures has been quantified to exceed the economic cost of the measures [33]. In general, an interdisciplinary approach should be used when assessing impacts from renewable energy sources on ecosystems [34], and some research indicate that such an approach facilitate solutions where both environmental improvements and economic advantages can be achieved [25].

Studies of economic impacts are case specific and sensitive to the available flexibility in the power system. Also, it is important to distinguish between system costs and the revenues of an operator when assessing economic impacts. If sufficient flexibility is available in the system, ramping rates may not have a significant impact on system costs [35], but the constrained power plant may see a loss of revenue. Furthermore, participation in several markets, such as provision of ancillary services, has been shown to impact the cost of environmental regulations [36]. Restrictions on minimum release, ramping rates and total water release have been found to have a significant effect on hydropower generation in off-peak and peak hours [37]. Several studies find an increase in cost when minimum flow and ramping constraints become more restrictive, [38], [39], [40], and for several cases the cost has been shown to increase linearly and quadratic with minimum flow and maximum ramping respectively [23]. In addition, the economic impact has been found to be larger in systems with higher price volatility for certain cases [41].

The reduced operational flexibility caused by ECs can also result in increased overall CO_2-emissions [42], [36]. By reducing the available flexibility from hydropower, other sources of flexibility have to be unlocked that potentially have higher CO_2-emissions. Similarly, it can become beneficial to reduce the flexibility contribution from hydropower in order to reduce the ecological costs if new sustainable sources of flexibility, e.g. demand response, is added to the system [43].

III. Environmental Constraints on Hydropower Operations

As discussed, environmental regulations can have large impacts on operation of hydropower plants and are therefore important to include in the operational planning models. Operational planning of hydro-dominated power systems applies models and methods that have matured over several decades [44]. The key task in systems with reservoir storage is to balance the optimal use of water in the short-term with the volumes stored for later use to minimize the expected operational cost of the system. The problem formulation should consider the characteristics of the system and the deployed constraints, planning horizon and temporal resolution. Some factors that typically increase the complexity of hydropower scheduling are: storage which make the problem dynamic in time, topology with dependencies between several reservoirs and power stations, physical characteristics that introduce nonlinearities (e.g. head dependencies), and uncertainty in inflow and power prices. The problem is typically divided into a long-term model and a short-term model because of the complexity and quickly growing size of the problem. The short-term model includes more operational details, while the long-term model has a longer planning horizon, includes uncertainty and sometimes also covers a wider geographical scope. The models are often linked together by a strategy for use of water which is calculated in the long-term model and used as a boundary condition to the short-term model. Sometimes a medium-term model is used to obtain a more detailed strategy calculation, i.e. refining water values from aggregated to individual reservoirs.

Environmental regulations can be considered in the modelling either through the objective function or through constraints which is the focus in this paper. An example of the former is multi-objective formulations and objectives based purely on ecological metrics [45], [46], [47]. ECs can be included in both long-, medium- and short-term modelling, but the formulation of the constraint have to be adjusted depending on the type of model and solution method, e.g. linear programming (LP), mixed integer LP (MILP) and non-linear programming (NLP) models.

A. Environmental Constraints

This section present the most common ECs used to regulate hydropower operations, as well as some more complex formulations. Other specific ECs also exist, such as constraints based on temperature limits [40] and water quality [48], [49]. The presented constraints are defined for each time step t in the planning horizon, T, if not otherwise specified.

1) Reservoir level constraints: restrict the reservoir level to be between defined boundaries by limiting the reservoir volume v_t to be in between the volume limits V^{min} and V^{max} [50], as given in (1). The reservoir limits can be defined for certain periods, i.e. time dependent boundaries.

$$V^{min} \leq v_t \leq V^{max} \tag{1}$$

2) Release constraints: limit the release from the power plant, i.e. discharge q^D and bypass q^B, to be in between certain boundaries, Q^{min} and Q^{max}, per time period [38]. The constraint can be on the total release as in (2), or defined specifically for bypass or discharge.

$$Q^{min} \leq q_t^D + q_t^B \leq Q^{max} \tag{2}$$

These constraints are typically defined as a constant minimum/maximum level, sometimes with seasonal variations (time dependent) [50]. More complex formulations of the constraint can be dependent on the water level in the reservoir or the inflow (see state-dependent constraints (9)) and/or on logical conditions (see constraints (7)- (8)). A slightly different definition of the release constraint occur when hydropower plants are required to release a specified amount of water Q^P over a given period (e.g. a month) [37], such as given in (3):

$$\sum_{t=\tau,..,\tau+N} (q_t^D + q_t^B) \geq Q^P \tag{3}$$

In the more extreme cases, release can be regulated as *mandatory run-of-river operation* [38], where the release is forced to equal the inflow Z_t as in (4). Run-of-river operation can be mandatory for parts of the planning horizon (e.g. certain weeks/moths), T', or the entire planning horizon, $T' = T$.

$$(q_t^D + q_t^B) = Z_t \tag{4}$$

3) River flow constraints: are often given as conditions on flow at a certain point in the river downstream of the power plant. For practical reasons flow constraints are normally implemented as a constraint on release. To account for the transportation time of flowing water, constant time delay between the reservoirs in the system is sometimes included. However, often a more accurate modelling of the physical flow in the river could be beneficial. To achieve an improved description, an alternative is to use a river routing approach based on streamflow routing curves [51]. The curves describe how different amounts of the water released from an upstream reservoir reach the downstream reservoir in different times based on empirical streamflow data. The improved flow modelling makes it possible to include constraints in specific river points, such as constraints on river level and hourly and daily variation in river level.

4) Ramping constraints: restrict the maximum change of plant release and reservoir volume between two successive time intervals. Rapid changes in flow downstream of the plant is avoided by constraining release or discharge [52], as given in (5). The maximum rate of change per time step is given by δ^{max}.

$$-\delta^{max} \leq q_t^D - q_{t-1}^D \leq \delta^{max} \tag{5}$$

Another objective of ramping constraints can be to limit how quickly the water level in the reservoir is permitted to be changed. The water level is a function of the water volume in the reservoir. Hence, the restriction can be enforced by constraining the decrease in reservoir volume v between two consecutive periods [53], as given in (6), or by applying a maximum discharge limit as given in (2). The maximum change in reservoir volume between two consecutive periods is given by γ^{max}.

$$-\gamma^{max} \leq v_t - v_{t-1} \leq \gamma^{max} \tag{6}$$

5) Logical constraints: refer to a set of constraints governed by logical conditions [54]. Given specific conditions constraints can be activated or deactivated, or the constraint formulation can be modified. An example can be that the maximum discharge level is lower *if* the reservoir level is below a certain threshold. Such conditions can normally be modeled by using binary variables. An example is given in (7)-(8), where the binary variable u_t is true ($= 1$) if the reservoir level v_t is above the reservoir level threshold $\frac{V^{max}}{2}$ and false (zero) if not [55].

$$q_t^D - (1 + u_t)\frac{Q^{max}}{2} \leq 0 \tag{7}$$

$$u_t \frac{V^{max}}{2} \leq v_{t-1} < (1 + u_t)\frac{V^{max}}{2} \tag{8}$$

6) State-dependent constraints: are constraints that depend on the value of one or more state variables in the problem formulation [56], e.g. reservoir volume and inflow [31]. Often such constraints also depend on logical conditions [55]. The previous discharge constraints (7)-(8) are state dependent as the discharge levels depend on the reservoir volume, i.e. the upper discharge level Q^{max} is a function of the reservoir volume v [54]. This can be expressed as:

$$q_t^D \leq Q^{max}(v) \tag{9}$$

7) Constraints dependent on the origin of the water: are constraints that become valid depending on when the water was accumulated in a reservoir or where the water originally came from. In such cases it can be necessary to keep track of the water present in the reservoir *before* a constraint became active, to keep track of the water accumulated *during* a constraint interval, or to keep track of water accumulated through a specific intake. Since the water may have different constraints dependent on *time* or *path*, the water within the same reservoir can be used differently and therefore also have different value. A possible approach to handle such constraints is to include virtual reservoirs in addition to the physical reservoirs in the modelling and calculate separate water values for the virtual reservoirs [57].

B. Modelling Challenges

More detailed operational constraints, such as ECs, are most commonly included in the modelling of the short-term problem. However, in hydropower dominated systems (e.g. the Nordic, the Brazilian and the Canadian), ECs may have an important impact on the overall flexibility in the system and should also be considered in the long-term planning. Even if the effect of a constraint on the system is limited, the impact on the long-term use of water in a reservoir could be significant and should be considered in the strategy. A main conclusion from the review in [23] was that minimum flow and maximum ramping rate constraints seldom were included in the water value calculation and the effect of such constraints on long-term operations was not estimated. The author demonstrated that such constraints have a significant impact on water values in some regions [50] and should be included in the calculation of medium to long-term strategies for water use [58]. If a constraint not significantly affects the medium- to long-term use of water, it may be sufficient to include it in the short-term models. In general, cautiousness of adding extra constraints to the problem is important to limit the problem size.

The long and medium-term hydropower scheduling problems are traditionally solved using LP and formal optimisation methods such as stochastic dynamic programming (SDP) [59] or stochastic dual dynamic programming (SDDP) [60]. A drawback of the SDDP method is that a convex problem formulation is required. Most ECs can be included in convex model formulations without considerable difficulty, such as constraints (1)-(6). However, state-dependent constraints (9) and logically conditioned constraints (7)-(8), introduce non-convexities into the problem. For an exact modelling of the non-convex medium term hydropower scheduling (MTHS) problem the SDDiP method [61] can be used [62]. The method is very time consuming, but has been used to solve the MTHS problem with non-convex ECs of type (9) in [56]. A more time efficient approach can be to represent complicating constraints with linear approximations [54]. In [63], an SDDP model is used to investigate trade-offs between multiple use of water by including irrigation withdrawals in the water balance. Furthermore, non-convex irrigation constraints included in a SDDP based approach has been found to give feasible solutions close to the optimal solutions determined by a MILP model [55]. The short-term models, including nonlinear and non-convex constraints, can normally be modelled exact [64], [65] or by using a wide range of heuristics and meta-heuristics [66] . In [58], a MILP short-term model is used together with a medium term, SDP based model to test the solution of the medium-term model and estimate the impact of including ECs in the water value calculation.

In methods based on dynamic programming (DP), preservation of constraints with bindings in time, such as constraint (5), (6), (8), or integral requirements like in constraint (3) can be a challenge between consecutive stages. In DP the problem is decomposed into several stages (e.g. weeks) with time steps on a finer resolution (e.g. hours) within each stage. As each stage normally is solved as a separate (sub)problem, flow constraints are not preserved from the last time step in one stage to the first time step in the following stage. This can give unwanted results, such as rapid ramping between stages. To ensure continuity across the stages for constraints of type (5), flow can be included as a state variable [23], or an heuristic approach can be used. For example can a simple rule-based method be used to set the flow in the first period of a stage equal the flow in the last period in the previous stage [67]. Reservoir volume is normally used as a state variable and constraints of type (6) will therefore change the calculation of cut coefficients in cut based methods such as SDDP. Some of the same challenges considering time couplings appears at the end of the planning horizon where the value of the affected variables can be set to be free or forced to take specified values.

The river flow is a crucial driver for ecological processes [7], still the water flow in the river between reservoirs are normally not modelled in hydropower scheduling models since accurate flow modelling is very complex. To improve the representation of flow in planning models for hydropower [68] suggest a non-linear function for water delay in cascaded hydro systems, while a river routing approach is used in [51] and [69]. The river routing approach has been demonstrated to yield a high accuracy in maximum daily and hourly river-level variations [51], as well as cost reductions as a result of improved coordination of hydropower generation [69]. In [70], a coupled reservoir operation and water diversion model is developed to consider the interaction of reservoir operation and downstream water diversions. The model is demonstrated to provide improved decision support to balance the ecological needs with other needs for water use.

IV. Concluding Remarks

Trade-offs between environmental benefits, economic costs and other consequences have to be considered when developing environmental regulations, as discussed in section II. For hydropower producers, expected higher price volatility will give increased value of flexibility compared to today and hence also higher costs of being imposed restrictions on own operation. This implies that accurate modelling becomes more important as the cost of model simplifications or inaccuracies can increase. Neglected or simplified model representations of ECs should therefore be revisited. In the long-term models, omitting or simplifying ECs can result in an overestimation of the flexibility of hydropower. In hydropower-dominated systems this could lead to problems for security of supply and potential high system costs. We find that there has been modest emphasis on accurate representation of ECs in long-term models in the technical literature, while such constraints more often are accurately handled in short-term models. Thus, there is a time-inconsistency [71] between long- and short-term models in the treatment of such constraints. As shown in section III, most of the ECs in use can be included in both long- and short-term operational models, but time couplings and non-convexities can be more demanding to model.

Based on the ecological considerations discussed in section I and II, it is clear that future operational conditions may be ecological demanding and environmental regulations are required. Improved knowledge over the last decades has made more exact formulation of the ECs to fit the primary ecological needs achievable, such as more dynamic constraints. Furthermore, in certain cases local knowledge can be used to achieve wanted ecological benefits, while also preserving most of the operational flexibility of the plants. In this context we find another trade-off. On one side, tailored constraints can minimize the impact on flexibility and associated cost while realising the wanted ecological benefit. But on the other side, tailored constraints make standardization difficult which again could make accurate modelling more resource demanding.

To conclude, we see that modelling of ECs in hydropower planning models has seen increased interest in the literature in the last decade. This can be a result of improved modelling methods and computational performance, which makes it possible to implement more complex constraints in operational models. Furthermore, the literature shows that improved modelling of ECs can be beneficial both from an environmental and economic perspective. Still, exact modelling of ECs can become hard or even impossible in operationally used models if modelling complexity is not considered in the formulation of the ECs. Model implementations can in turn provide poor ecological performance if not considering the underlying purpose of the ECs. Hence, cross-disciplinary knowledge is necessary to achieve environmental regulations that perform well both considering ecology and economy. When succeeded, previous projects have shown that it is possible to realise win-win situations.

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