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Grid-wide subdaily hydrologic alteration under massive wind power penetration in Chile

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ABSTRACT

Hydropeaking operations can severely degrade ecosystems. As variable renewable sources (e.g. wind power) are integrated into a power grid, fluctuations in the generation-demand balance are expected to increase. In this context, compensating technologies, notably hydropower reservoir plants, could operate in a stronger peaking scheme. This issue calls for an integrated modeling of the entire power system, including not only hydropower reservoirs, but also all other plants. A novel methodology to study the link between the short-term variability of renewable energies and the subdaily hydrologic alteration, due to hydropower reservoir operations is presented. Grid operations under selected wind power portfolios are simulated using a short-term hydro-thermal coordination tool. The resulting turbined flows by relevant reservoir plants are then compared in terms of the Richard-Baker flashiness index to both the baseline and the natural flow regime. Those are then analyzed in order to: i) detect if there is a significant change in the degree of subdaily hydrologic alteration (SDHA) due to a larger wind penetration, and ii) identify which rivers are most affected. The proposed scheme is applied to Chile's Central Interconnect System (SIC) for scenarios up to 15% of wind energy penetration. Results show a major degree of SDHA under the baseline as compared to the natural regime. As wind power increases, so does the SDHA in two important rivers. This suggests a need for further ecological studies in those rivers, along with an analysis of operational constraints to limit the SDHA.

1. Introduction

As population growth and green policies demand increasing levels of renewable energy in power systems, deployment of variable energy sources, such as wind power, is rising quickly worldwide (International Energy Agency, 2014). However, their power output is highly fluctuating on short time scales, and requires compensation by other power plants of the grid, particularly those fast-responding units as hydropower reservoirs (Carvalho et al., 2011). The resulting, highly fluctuating operational scheme, known as hydropeaking, has been proven to severely affect ecosystems (Bruno et al., 2009; Hunter, 1992; Poff and Zimmerman, 2010; Richter et al., 1997; Saltveit et al., 2001; Tuhtan et al., 2012). Impacts include washing-out and stranding of species (Petts, 1985), life cycle disruption (Scheidegger and Bain, 1995), threads to native species (Stanford et al., 1996), change in vegetation and food web structures (Wootton et al., 1996), among many others. Nowadays, the most popular approach to address the issue of altered flows relies on the Indicators of Hydrologic Alteration (IHA) (Richter et al., 1996). As a certain level of variability of flows is normal and healthy for a river (Lundquist and Cayan, 2002; Poff et al., 1997), the Range of Variability Approach (RVA) compares samples of these indexes before and after human intervention (Richter et al., 1997). However, the IHA approach uses daily flow measures, which cannot capture the subdaily fluctuations caused by hydropeaking (Baker et al., 2004; Bevelhimer et al., 2014; Haas et al., 2014; Zimmerman et al., 2010). Recently, Bevelhimer et al. (2014) found that the indexes based on daily flows are not correlated with metrics of subdaily hydrologic alteration. Moreover, Kern et al. (2012) pointed out that previous IHA studies focused on traditional hydropower scheduling with well-known periodicity (i.e. in the short term one or two major peaks per day), as opposed to a more variable operation induced by economic incentives within deregulated power markets. This could be further exacerbated by larger penetration of fluctuating renewables.

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Since commonly hydropower reservoir operations are part of an intertied power grid, properly simulating their operation requires modeling the whole grid, as flexibility could be provided among many other power plants. This challenges, however, the traditional *plant to plant* or basin-wide approach.

This paper proposes a framework to assess SDHA of reservoir operations under massive wind penetration scenarios, based on a power system dispatch model. The proposed methodology is, to the author's knowledge, the first attempt to analyze grid-wide SDHA. The framework is exemplified through a case study in Chile, results which might shed light on the relevant tradeoffs between techno-economic objectives and environmental impacts for policy makers.

The work is organized into five sections. The proposed methodology is described in Section 2. Section 3 includes a detailed description of the case study, with results discussed in Section 4. Finally, conclusions and future work are presented in Section 5.

2. Proposed methodology

2.1. General framework

This paper proposes a general framework to study increased SDHA induced by a variable operation of hydropower reservoirs, when fluctuating renewable energy sources are massively introduced in a power system. The proposed methodology comprises 5 main steps, as shown in Fig. 1.

To allow for a comparative analysis, Step 1 aims to determine the current and the natural degree of SDHA of the whole system under study. To adequately capture the variability of primary energy and hydropeaking operations, this analysis should rely on hourly data (Holttinen, 2005). In this context, data availability and management can be challenging due to the required time resolution and spatial distribution. The flow data is then used to compute the SDHA indexes of the natural regime and current situation.

In Step 2, scenarios of different levels of renewable energy integration are defined. This step involves considering specific plant location as spatial and time correlations of primary energy are likely to exist, both between new renewable projects and existing hydropower plants.

To simulate hydropower operations, Step 3 consists in formulating and implementing a grid-wide coordination model. To fully capture the relevant dynamics of the system, attention should be paid to the time resolution, planning horizon, forecasts and variability of primary energy, representation of hydraulic connectivity, alternative water uses (e.g. irrigation), flow routing times, regulation capacity at different time-scales, and market distortions (e.g. subsidies or oligopolies) and participation. Power demand, as it is highly dynamic at different time scales, must be represented with at least an hourly resolution.

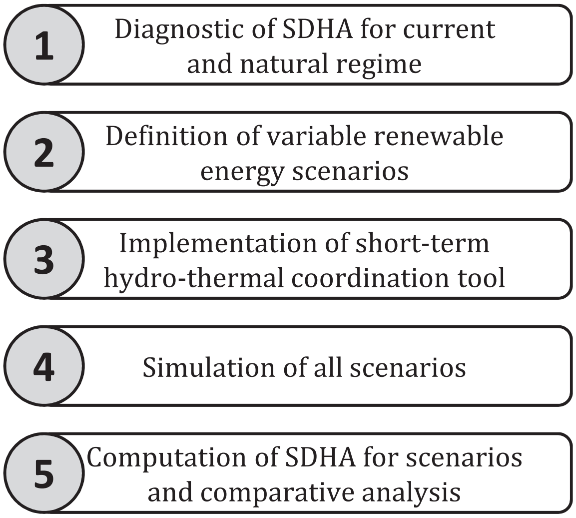

Fig. 1. 5-step proposed methodology.

In Step 4 the power dispatch tool in run for all previously defined scenarios. Large amounts of data and computing times are to be expected as a grid-wide model is used. The relevant outputs are hourly time series of power production at each power plant in the grid. For hydropower plants, turbined flows are computed.

Step 5 computes the SDHA indexes from hourly flows in the modeled scenarios along with the analysis of results. The resulting SDHA indexes of the different cases are then compared, including the baseline and the natural regime. At this point, additional analyses can be performed to assess the tradeoffs between techno-economic and environmental performance.

2.2. R–B Index of SDHA

Among the SDHA indexes used by Zimmerman et al. (2010), the 'R–B Index' (Baker et al., 2004) is the only one that captures the magnitude of multi-ramping events within a day, while considering the sequence of flows. Hence, this indicator was chosen for the present study. The R–B Index (Equation (1)) computes the path length of variations in flow *q* between time steps *t*, divided in the total daily flow of the period. In this study, an hourly resolution of the index is used to capture the main components of wind variability.

$$\mathrm{R-B\ Index} = \frac{\sum_{t=1}^{T}\left(|q_{t+1}-q_t| + |q_t-q_{t-1}|\right)}{2\cdot\sum_{t=1}^{T}q_t} \tag{1}$$

3. Description of the case study

The previously proposed methodology is applied to Chile's main grid, the Central Interconnect System (SIC), which is structured as a pool system with audited costs. Therefore, the operation of hydropower reservoirs is centrally prescribed as resulting from a cost-minimization model run by the system operator (ISO).

The grid configuration as of end 2012 was used, presenting a peak demand of 7 GW and 13 GW of installed capacity. It was composed by 50% thermal generators, 43% large hydropower plants, 2.5% wind farms, and 4.5% of other small renewables. Hydro units located in the center-south of the country serve the load centers of the central zone, as seen in Fig. 2. Wind farms are projected along the coast, but concentrated in the center-south and center-north.

The system has over 100 hydropower plants. However, only 9 of them possess major reservoirs. Two of those restitute their outflow close to -or directly into-the sea. Hence hydrologic alteration might be less relevant for their river systems and they are not analyzed in this study. The remaining 7 conform three major hydropower systems of about 1000 MW each: *i*) 'Maule' composed by 'Cipreses', 'Pehuenche', 'Colbún' and 'Machicura', the latter being the most downstream reservoir of the basin; *ii*) 'Laja', with 'El Toro' reservoir and downstream run of river plants; and *iii*) 'Alto Bío-Bío' composed by 'Ralco' and 'Pangue', with Pangue being the last reservoir of the series. Table 1 summarizes this information and in addition displays basin size, power capacity of the plants and reservoir capacity.

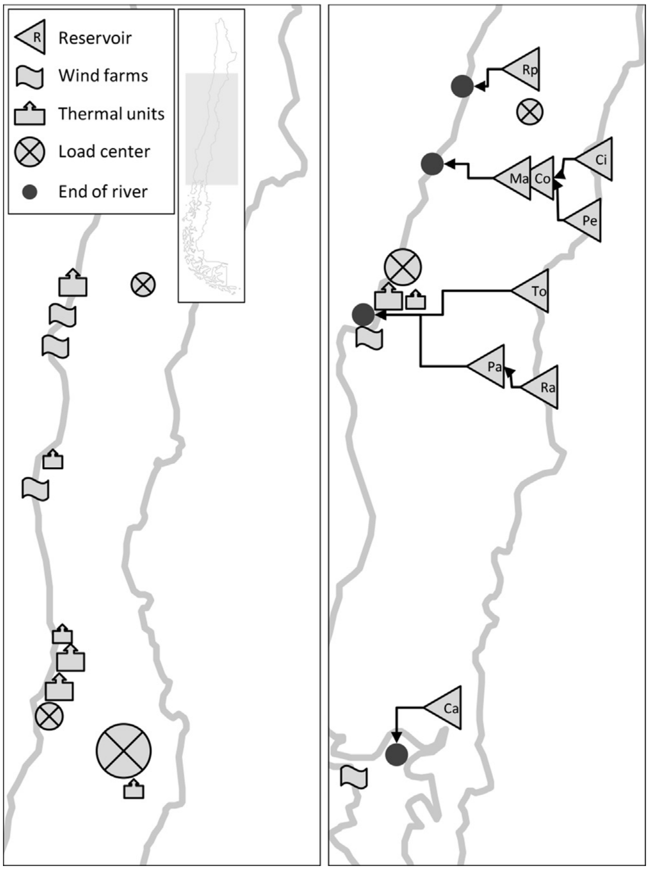

Fig. 2. Simplified schematic of central Chile's reservoirs, load centers, (aggregated) thermal units and (aggregated) projected wind farms.

Table 1
Power capacity, storage capacity (Power System Operator of Chile (CDEC), 2013) and basin size (National Directorate for Water of Chile, 2013) of main hydropower reservoirs of Chile's SIC. Lowest reservoir of each basin in bold.

Hydro reservoir	Symbol on Fig. 2	Name of basin	Power capacity [MW]	Basin size [km^2]	Storage capacity [M m^3]
Cipreses	Ci	Maule	100	940	170
Pehuenche	Pe	Maule	560	2300	130
Colbún	Co	Maule	450	5750	1550
Machicura	Ma	Maule	95	5750	20
El Toro	To	Laja	450	1470	5590
Ralco	Ra	Alto Biobío	690	5110	1170
Pangue	Pa	Alto Biobío	450	5430	70
Canutillar[a]	Ca	–	170	340	1070
Rapel[a]	Rl	–	375	13,280	560

[a] Restitution point is close to ocean.

3.1. Diagnostic of SDHA for current and natural regime

In Chile, minimum flows are only compulsory for projects built after 2005 (Minsitry of Public Works of Chile (MOP), 2005), although some older plants have come to voluntary agreements. Thus, turbined flows are the main component of instream flows, downstream of the generators. Water is also used strongly for irrigation purposes. Consequently, basically every stream northern of Biobío River is intervened downstream of the central valley. Hence, determining the natural flow regime for the whole river is a complex task as data with proper resolution is scarce for the time in which intervention was neglectable. Fortunately, in higher sections of each river -where most of the reservoirs are-, hourly data of the last decade are public for many stations (National Directorate for Water of Chile, 2013). On the other hand, the current operation will be described with flow data resulting from the baseline computed with the hydro-thermal coordination tool. The baseline will be used as a reference in order to make a valid comparison with the operation under renewable energy scenarios defined in the next section.

3.2. Definition of variable renewable energy scenarios

Aligned with Chile's renewable goal 20/25 (20% of unconventional renewable energy by year 2025), many wind power projects are currently being built, have recently passed the environmental assessment or are under evaluation. In this context, three gradually increasing wind portfolios were defined: *i*) 'Wind 1' of 300 MW, representing the existent (as of June 2013) wind farms; *ii*) 'Wind 2' of 1000 MW including existing farms and projects under construction or likely to be constructed within the next couple of years; and *iii*) 'Wind 3' of 3200 MW containing the aforementioned plants, in addition to all other projects with environmental permits (SEA, 2013). Wind 1 allows for analyzing the current situation (baseline); Wind 2, the near future, when construction of the projects is finished; and Wind 3 the optimistic wind penetration scenario (~15% wind energy penetration), in which all the approved projects get built.

Each project of the portfolios accounts for the wind speed profile of the installation site, connection point to the grid, height and power curve as informed in its environmental assessment (SEA, 2013). As the three portfolios are very heterogeneous, in capacity and geographic dispersion, the spatial variability of wind is already captured. Hence, it is not strictly necessary to perform a sensitivity analysis regarding different wind profiles. This is illustrated in Fig. 3, where the upper plot shows the power output of wind portfolio 1, 2 and 3 during one month (January 2006), while the lower plot compares three different wind profiles (January of 2006, 2007 and 2008) of portfolio 2. Although an important variability

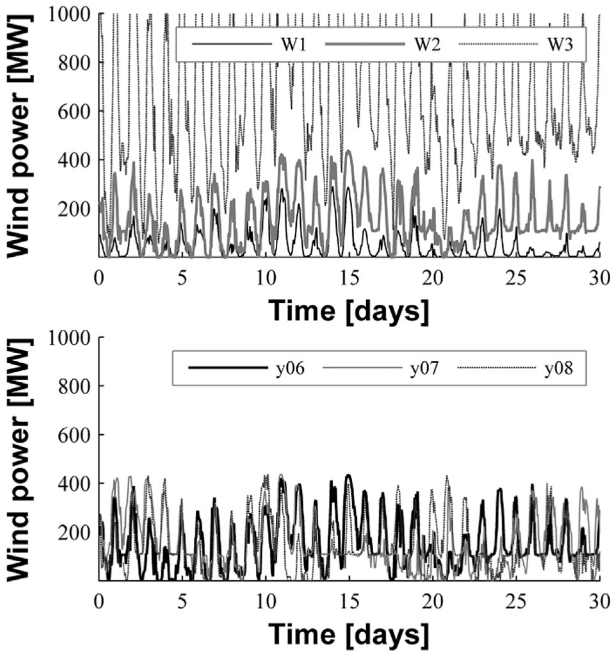

Fig. 3. Upper plot: wind power variability of profile January 2006 for portfolio 1, 2 and 3. Lower plot: variability of portfolio 1 for different wind profiles (January of Year 2006, 2007 and 2008).

exists between different wind profiles for a given month, the ramps between the wind portfolios are more significant. After analyzing the mean, standard deviation, and sum of ramps of the available wind power for the different years of available information (1980–2012), year 2006 is chosen as an average year. For the simulations, perfect forecast of wind is used, hence the challenge of predicting wind is not considered within this study.

3.3. *Implementation of short term hydro-thermal coordination tool*

Chile's ISO currently uses a deterministic mixed integer optimization to prescribe the economic operation the power system. Hence, a replica of this model was used (Benavides, 2008), so the results can be as close as possible to current practice. The model considers every main power plant of the grid, taking into account power capacity constraints, electrical and hydraulic connectivity, water inflows, generation costs, ramp rates, minimum on/off times, among other inputs. It is noteworthy that ramp rates are not active constraints in the SIC, however on/off times are.

As the electricity sector of Chile consists in a pool with audited costs, market distortions in the weekly scheduling due to market power exerted by specific agents, should not occur in theory. Participation of the hydropower plants in the day-ahead planning is considered.

Consistent with the deterministic nature of the model, a scenario approach was chosen to study the effect of inflow patterns on the SDHA. A wet, normal and dry water type year, using historical years with a probability of exceedance of annual flows of 20%, 50% and 90%, were defined.

Regarding the variability of load, the weekly simulation horizon of the tool already contains the intra-daily cycles and the weekday/weekend profiles. To include the seasonal variability, one typical week per month was used.

Consequently, three wind portfolios and three water type years were defined, forming 9 combined scenarios. Each of them is composed by 12 representative weeks. For these 12 weeks, for all 9 scenarios, the system's hydro-thermal scheduling is computed.

For the main reservoirs, the initial water storage volumes and opportunity cost of water must be defined for each week and scenario. For the first, the historical records of stored water of each reservoir were filtered according to water type year and the median of the resulting set was chosen. For the latter, the future cost functions of every selected week, computed by the ISO (2013) using a mid-term planning model based on stochastic dual dynamic programing (Pereira and Pinto, 1991), were used. Those were not updated for the different wind portfolios, which is a limitation of this work.

3.4. *Simulation of all scenarios*

The inputs are mainly obtained from the Chile's ISO (2013). When applied to the SIC, 100 hydropower plants, 100 thermal generators (including biomass), 180 power lines and 140 power nodes are modeled. This generates an optimization problem with approximately 700.000 continuous decision variables, 10.000 binary variables, and 100.000 constraints. The MIP convergence criterion was set to a relative gap of 0.0001%. To reach the optimality, using CPLEX® with an i7-3770 processor and 24 GB memory computer, between 4 and 24 h are required for each computed week. After simulating all the cases the power time series are available for postprocessing.

3.5. *Computation of SDHA for scenarios and comparative analysis*

The power time series of the simulated scenarios are translated into instream flows for every hydropower plant. With these, the R–B Index is computed, first using hourly and then daily resolution. The analysis of the resulting indexes is discussed in the next section.

4. Results and discussion

The analysis of results is divided in two parts. First, the importance of the hourly time resolution on R–B Indexes is underlined by comparing the indexes of daily and hourly resolution for the baseline, summarized in one index for a whole year. Second, the effect of wind power on SDHA of rivers downstream of hydropower reservoirs is analyzed, using duration curves composed of R–B Indexes of hourly resolution -one per day-, for all computed scenarios.

4.1. *Comparison between R–B Index on daily and hourly basis*

Traditionally, when determining ecological flows, data with daily resolution is used. As shown by Zimmerman et al. (2010), this is insufficient as strong fluctuations can occur within a day. This was also found for Chile. For example, 'Pangue' operates on a strong hydropeaking regime and controls a large fraction of an important river of Chile. Although the hourly discharges are largely variable, they are barely perceived when daily averages are used, as illustrated in Fig. 4. To quantify this effect, yearly SDHA indexes with hourly and daily resolution are computed and shown in Table 2. As the denominator of the index is the same for both cases, the ratio of the indexes is equal to the ratio between the hourly and daily path lengths.

All of the reservoirs exhibit a much larger index when hourly resolution is used. Although this is consistent with the findings of Baker et al. (2004), in this study the ratio between the R–B Indexes of different time resolution is much larger. For example, 'Colbún' and 'Rapel' show to have a subdaily peaking 14 times stronger than their values based on daily resolution. Consequently, definition of environmental flows on daily averages might be insufficient, as subdaily operation can exhibit severe fluctuations, which are masked in the daily resolution. In this context, the recent legislative change in the method for determining environmental flows in Chile needs to be revised as it is based on daily averages.

4.2. *Hourly R–B Index*

To study the hydrologic alteration, duration curves (sorting values from greater to smaller) are used, as there is a large amount of indexes for each scenario. The loss of time correlation in the duration curves is not significant as the structure of the index

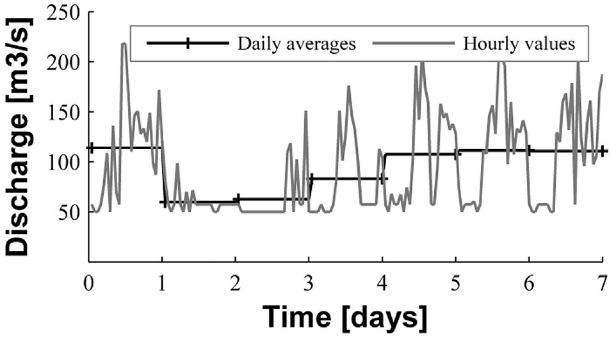

Fig. 4. Daily averaged discharges and hourly discharges of hydropower reservoir 'Pangue' for a given week of a normal hydrology.

Table 2
R–B Index computed with hourly flows and daily average flows, and ratio between those two, for main hydroreservoirs.

Hydro reservoir	Hourly R–B Index	Daily R–B Index	Ratio (hourly/daily)
Cipreses	0.051	0.007	7.2
Pehuenche	0.133	0.011	11.9
Colbún	0.148	0.010	14.8
Machicura	0.095	0.007	13.0
El Toro	0.014	0.002	6.1
Ralco	0.050	0.009	5.5
Pangue	0.114	0.010	11.2

makes it time and discharge independent. Four R–B series are plotted: *i*) natural regime; *ii*) operation under portfolio 'Wind 1' (baseline); *iii*) operation under portfolio 'Wind 2'; and *iv*) operation under portfolio 'Wind 3'.

An example of the resulting plots is shown in Fig. 5. Here the R–B Index of the largest hydropower reservoir ('El Toro') is displayed. It compares the flow alteration between the natural regime (thick black line), portfolio 'Wind 1' (thin black line), 'Wind 2' (thin gray line) and 'Wind 3' (thin dashed line). If a R–B threshold of 0.05 was used (Zimmerman et al., 2010), it could be observed that this value is currently being exceeded 56% of time (i.e. ~204 days a year), but under wind portfolio 2 and 3 it would be exceeded up to 63% (~229 days a year) and 65% (~237 days a year) of time, respectively. Although this is a relative increase over 12% due to wind power, the main issue appears to be the large deviation between the baseline and the natural regime: 56% vs 22%, respectively. For larger values of R–B Index, the effect becomes more evident. For example, R–B values of 0.25 are exceeded only 1% in the natural regime, but 9%, 12% and 25% of the time, in the case of 'Wind 1', 'Wind 2' and 'Wind 3', respectively. These are significant differences when compared to the natural regime. Finally, it can be noted that high fluctuating events become stronger: the maximum index of the natural regime is equal to 0.5, while for portfolio 'Wind 1', 'Wind 2' and 'Wind 3' it is 0.6, 0.75 and above 1, respectively. Finding an ecological significant threshold of the R–B Index is still an open challenge.

The previous analysis is extended for the remaining power reservoirs of the system (plotted in the rows of Fig. 6) and the dry, normal and wet water type years (left, middle and right column of Fig. 6, respectively). A strong peaking scheme can be observed for all reservoirs. Concurrently, they are far distant from the natural regime both in terms of frequency of any given R–B Index and the maximum value of the index.

The 'Colbún-Machicura' system, in a year of average flows, shows a consistent trend of increasing SDHA. Luckily, the effect is smaller in the most downstream reservoir 'Machicura'. During dry and humid years, the wind-induced increment in SDHA is only clear for reservoir 'Colbún'. Curiously, 'Machicura' shows an improvement in wet year. One reason for this can be the great availability of water in the entire system, which distributes the peaking among all hydro units and allows 'Machicura' to operate with smaller peaks facilitating the fulfillment of irrigation agreements.

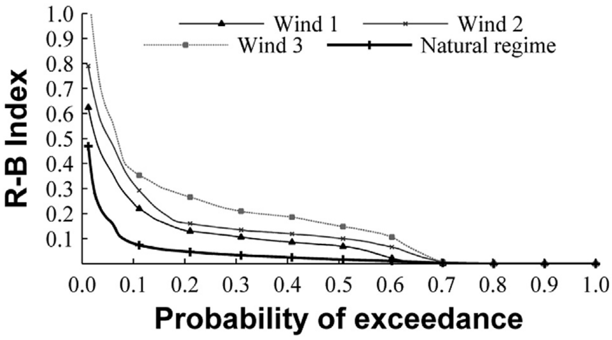

Fig. 5. SDHA index of hydropower reservoir "El Toro" in a wet year for the natural regime and the three wind power portfolios.

'El Toro' is the only reservoir where the baseline is closer to the natural regime, for normal and wet years. However, it shows a consistent increase of SDHA as wind energy enters the grid. As 'El Toro' is the only inter-annual reservoir, it is expected to deliver significant amounts of energy through time, which, together with large releases enforced by irrigation agreements, induce more regular operation.

The system 'Ralco-Pangue' shows a mixed behavior. While 'Ralco' improves its SDHA indexes during dry and average years, 'Pangue' shows a strong increase in its indexes. However, both are insensitive to wind scenarios in wet years. This behavior can be explained when analyzing more closely their operation. 'Ralco' as a larger reservoir tends to save water during the first half of the hydrologic year. Thus, it operates at very low power outputs many weeks of that period, especially for dry and normal years. The amount of wind in the system does not alter this situation. On the other hand, 'Pangue', having a much smaller reservoir, receives the ecological flow of 'Ralco', which must be turbined to avoid spillages. This generation tends to be more fluctuating for large wind scenarios than for the current situation.

In conclusion, 'El Toro', 'Pangue' and 'Colbún' are the most sensitive hydropower plants as they are negatively affected under almost every wind scenarios. Moreover, since 'El Toro' and 'Pangue' are the most downstream reservoir of their basin, their operations affect the whole downstream river system. On the other hand, the fluctuations of 'Colbún' are absorbed by 'Machicura', which fortunately is insensitive to important wind ramps. Finally, although wind does induce a greater flashiness in hydro reservoir operations, this increase is rather small in the context of the large contrast between the baseline and the natural regime.

The analyzed reservoirs exhibit quite dissimilar operations, when compared to each other. This difference in operation is much more significant than the one induced by wind portfolios or water type years. Hence, for environmental assessments, projects should be analyzed individually and operation schemes accounted for, but always tied to grid operation. As noted, some of the results are not intuitive and likely explained by hidden system dependencies. This emphasizes the need for a grid-wide analysis when dealing with hydropower reservoir operations and its effects in terms of subdaily hydrologic alteration.

5. Conclusions and future work

This paper studies the effect of wind power integration on hydropower reservoir operations, in terms of subdaily hydrologic alteration (SDHA). The proposed method includes five steps: SDHA diagnostics, definition of wind power scenarios, development of a subdaily grid-wide scheduling model, scenario simulation, and comparative analysis. This approach can be used to identify rivers sensitive to variable renewable energy integration, which is helpful for ecosystemic studies.

The method is illustrated through a case study applied to Chile. The baseline and two additional wind development scenarios are compared to the natural flow regime, using a grid-wide, cost-minimization hourly power dispatch tool for three water type years.

Results show that indexes based on hourly data are up to 14 times higher than those from daily flows, underlining the importance of the time resolution. As to the effect of wind penetration on SDHA, more wind usually implies more alteration, although the effects are not uniformly distributed among all the reservoirs. In

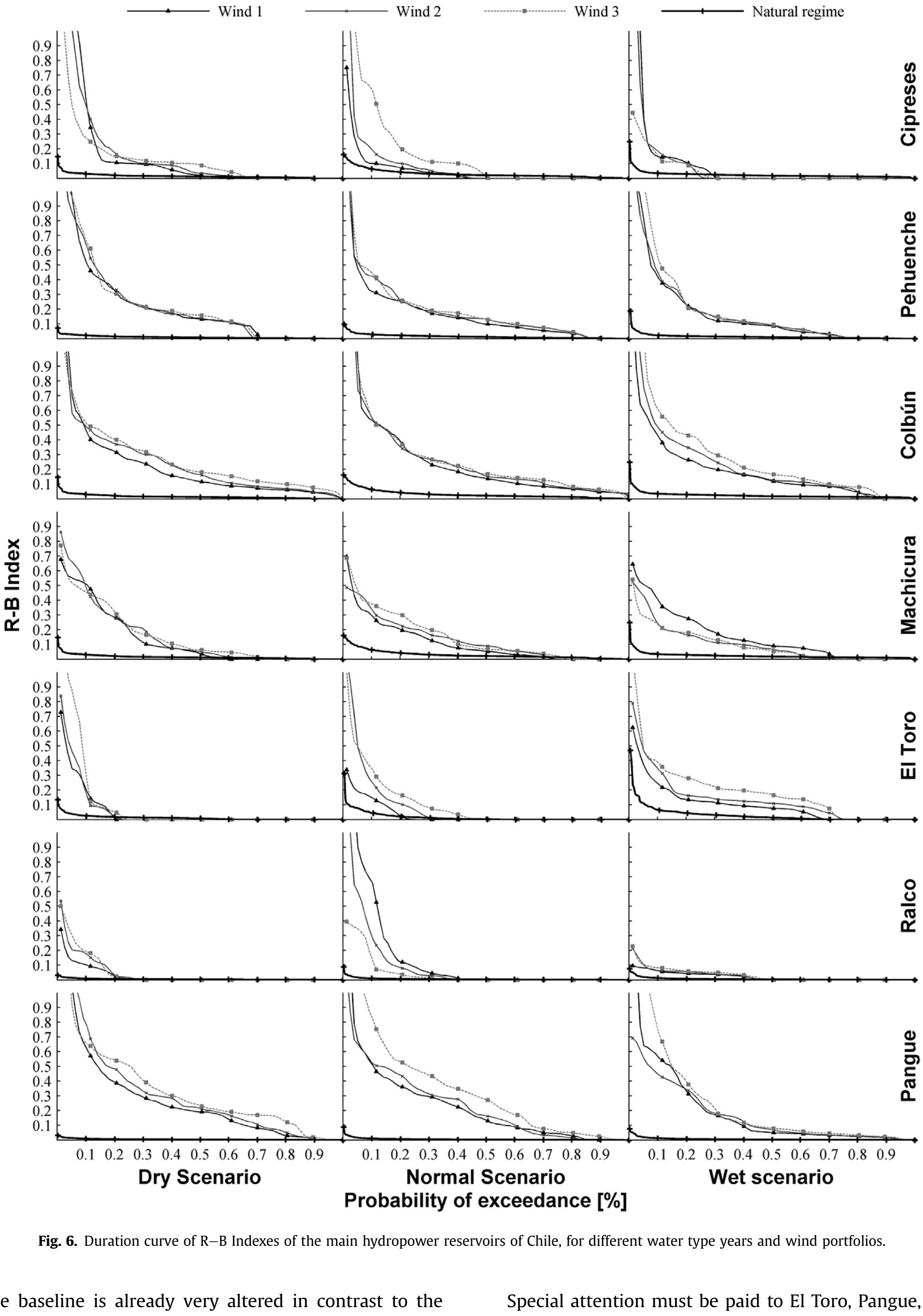

Fig. 6. Duration curve of R–B Indexes of the main hydropower reservoirs of Chile, for different water type years and wind portfolios.

addition, the baseline is already very altered in contrast to the natural flow regime, having the wind only marginal effects on SDHA.

Regarding the effect of water type years, for normal years, the trend of most of the reservoirs is to intensify their SDHA indexes. For dry years, the effect of wind on the power reservoirs is less intense and for wet scenarios it shows a mixed behavior.

Special attention must be paid to El Toro, Pangue, and Machicura, as they are the reservoir most downstream of their basins. Consequently, they should be studied more closely from an ecosystemic point of view, to ensure the future health of the river system.

The analyzed power reservoirs show very different operation schemes when compared to each other. This inter-power plant variation is much stronger than the difference in fluctuations induced by wind portfolios or water type years. For environmental assessments, this calls for individual project analysis, but always tied to grid operation, in which operational constraints and physical countermeasures (Olivares, 2008; Pérez-Díaz et al., 2010) should be evaluated to reduce hydrologic alteration.

For further statistical evidence a set of new scenarios, modifying demand, renewable energy penetration levels, forecast capability, energy mix of power system and expansion of transmission lines could be explored. Specially, extending the analysis to solar PV, as a strong correlation between the primary energy exists, is also proposed.

Acknowledgments

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