System Adequacy in Hydro Rich Countries: Proposing an Energy Aware Indicator

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1. Introduction

The assessment of the ability of the power system to satisfy electricity demand (system adequacy) has been traditionally based on comparing peak-load to available capacities. With an increase in the share of variable renewable energy sources (vRES), methodologies to assess system adequacy have been refined in recent years. In this process, the European Network of Transmission System Operators for Electricity (ENTSO-E) has for example continuously updated their target methodology for Adequacy Assessments. Based on a comprehensive probabilistic analysis, the latest Mid-Term Adequacy Forecast Report (ENTSO-E 2017) relies on three main indicators for generation adequacy, describing the energy not served in MWh per year due to insufficient available generation and import capacities to satisfy demand (ENS), loss of load expectation as the number of hours per year where demand cannot be satisfied (LOLE) and the probability of a loss of load event at a given time (LOLP). While stochastic, model based approaches such as the one used by ENTSO-E seem to be well suited for pan-European assessments, most system adequacy indicators focusing on comparing available generation capacity to expected load to calculate the probability, frequency or severity of loss of load events (JRC 2016), have neglected the particularities of mostly hydro-based systems.

In such systems (e.g. the Swiss or Norwegian power system), the amount of water stored in reservoirs for electricity production from storage hydro facilities represents a crucial determinant of system adequacy, as a lack of stored energy in storage lakes can significantly reduce the generation capacity actually at disposal of market actors and system operators. We therefore propose a new set of complementary indicators of system adequacy that represent the number of hours a hydro rich electricity system is able to cover its load without imports (i.e. under an import disruption scenario) from neighbouring countries (duration of storage supply; DSS) and the buffer of storage supply for different time horizons of import disruption (buffer of storage supply; BSS). The indicators have two major strands of application. On the one hand, they allow for an analysis of long-term planning of investments into storage and generation capacities. On the other hand, they can be applied to more short term planning to identify possible shortage situations under different weather dependent demand and supply scenarios to adapt intra-annual storage operation.

The analysis in our paper is twofold. In the first part, we first present the literature on existing system adequacy indicators and their usage by European regulators and supranational organisations before introducing our own indicator that takes hydropower storage contents and its relevance to system adequacy into account. In the second part, we present an exemplary application of the newly developed indicator to the Swiss electricity system. To this end, we use a nodal pricing DC load-flow electricity dispatch model for Switzerland (Swissmod; Schlecht and Weigt, 2014).

2. System Adequacy Indicators

In order to measure the adequacy of an electricity system a variety of indicators exist. Depending on the scope of the system adequacy (SA) studies, three functional zones of electricity systems have to be distinguished. The resource adequacy level (or hierarchical level I) considers the total generation as well as the cross-border transmission (NTCs). The transmission adequacy level (or hierarchical level II) includes the generation and transmission in the SA analysis. The overall hierarchical level (or hierarchical level III) involves all three functional zones, that is generation, transmission and distribution (Entsoe, 2016). Independent of the functional zones, SA indicators differ in the underlying approach or model which is used in their simulation. While some indicators are calculated by deterministic approaches other indicators are probabilistic (Poncela-Blanco et al., 2016). An overview of common SA indicators is shown in Table 1.

Table I: Overview of SA Indicators.

Indicators:	*Definition:*	*Model:*	*Sources:*
Expected Energy not Served (EENS)	Lost Load in GWh per year	probabilistic	Penta, 2015; Entsoe, 2016; EC, 2016a; Poncela-Blanco et al., 2016

Loss of Load Expectation (LOLE)	Number of hours per year with lost load	probabilistic	Penta, 2015; Entsoe, 2014; Entsoe, 2016; EC, 2016a; Poncela-Blanco et al., 2016
Loss of Load Probability (LOLP)	Probability of lost load	probabilistic	Penta, 2015; Entsoe, 2014; EC, 2016a; Poncela-Blanco et al., 2016
Loss of Energy Probability (LOEP)	Ratio of EENS and total demand	probabilistic	Poncela-Blanco et al., 2016
Reserve Capacity Margin (RCM)	Excess of available capacity with respect to demand	deterministic	Penta, 2015; Entsoe, 2017; EC, 2016a; Poncela-Blanco et al., 2016
Downward regulation	Excess inflexible generation during low demand periods	deterministic/ probabilistic	Entsoe, 2017
Full load hours of generation	Full load hours of operation per technology	deterministic/ probabilistic	Entsoe, 2014
RES curtailment	Level of RES curtailment	deterministic/ probabilistic	Entsoe, 2014
Frequency and duration of expected outages	Probability and time for which a generator is out of service	probabilistic	EC, 2016a; Poncela-Blanco et al., 2016
Equivalent firm capacity	Renewable capacity able to maintain the same LOLE	probabilistic	EC, 2016a
Coverage Index	Ratio between the available generation capacity and the peak load	deterministic	Poncela-Blanco et al., 2016
Largest unit	Difference between total installed capacity and the peak load compared to largest unit	deterministic	Poncela-Blanco et al., 2016

Out of the indicators from Table 1, EENS, LOLE, LOLP and RCM are the ones most often used in practice in analysing SA. Since the individual indicators give different insights, multiple indicators are often used in combination (Poncela-Blanco et al., 2016; EC, 2016a). Great Britain, France and Portugal for example use i.a. EENS as well as LOLE in their national SA analyses. The individual indicators which are applied are compared to target values in order to evaluate the SA risk. However, the target values can be country-specific. While e.g. Great Britain and France have defined a target value for LOLE of 3 hours, Portugal has a LOLE target value of 8 hours (Poncela-Blanco et al., 2016).

On European level, Entsoe (2014) defines a target methodology for adequacy assessment in the Entsoe area. Beside additional indicators, LOLE and LOLP are the main SA indicators proposed by the Entsoe target methodology. In the mid-term adequacy forecast of Entsoe (2016) especially EENS and LOLE are used to evaluate the SA situation of the Entsoe member countries. In the summer outlook 2017 by Entsoe (2017) in turn, the remaining capacity (upward adequacy) as well as the excess inflexible generation during low demand periods (downward regulation) are considered in simulating the potential risk to system adequacy in the Entsoe area. While the Entsoe SA studies are on national or European level, the Pentalateral Forum (Penta) studied the SA situation of the PLEF region (France, Germany, Austria, Switzerland, Netherlands, Belgium and Luxembourg) in more detail on a region level. Thereby, LOLE, LOLP, EENS as well as the RCM were used as main SA indicators (Penta, 2015).

3. New Indicator for Hydro Rich Countries

In an electricity system dominated by hydropower, such as that of Switzerland, storage reservoirs play an important role in the security of supply. In order to take into account and quantify the role of storage reservoirs in terms of supply security, two new indicators are developed. The *duration of storage supply* (DSS) quantifies how many hours a national electricity system can be supplied autonomously through the energy stored in the domestic reservoirs. The indicator thus measures for how many hours of a week, a month or a year the energy stored in the reservoirs is sufficient to cover the residual load (total domestic load minus dispatchable and non-dispatchable generation other than storage hydropower) under the assumption that net imports are not possible. A second indicator, *buffer of storage supply* (BSS) in MWh is defined for given target time periods of autonomous domestic supply and calculates the buffer (or gap, if negative) that storage reservoirs exhibit in excess of what is needed to self-supply the country for a given amount of time. BSS therefore gives an indication of how close the system gets to a situation where self-supply for the given amount of time is no longer possible.

The first indicator, duration of storage supply (DSS), is measured in hours and defined as the number of hours a system is able to run without imports, i.e. to cover net load (load minus dispatchable and non-dispatchable generation other than storage hydropower) by energy stored in storage reservoirs without any imports. The indicator therefore captures the resilience of a hydro rich country's electricity system against import disruption scenarios.

$$DSS_t = \sum_{h=t}^{T+t} g_{t,h}$$

$$g_{t,h} = \begin{cases} 1 & if\ S_t \geq D_{t,h} \\ 0 & if\ S_t < D_{t,h} \end{cases}$$

$$S_t = \text{Energy content of storage in MWh in } t$$

$$D_{t,h} = \text{Cumulated residual load in MWh from } t \text{ to } h$$

The buffer of storage supply (BSS) on the other hand is measured in MWh and defined as the amount by which the energy content in the storage reservoirs exceeds (or falls short of, in case of negative values) the amount of energy needed to supply the domestic electricity system for a desired amount of time. The desired amount of time (the target self-sufficiency timeframe) is needed as an external input for the calculation of the indicator. We propose the calculation of the indicator for different self-sufficiency target periods and in this paper calculate weekly, fortnightly, monthly and bimonthly BSS indicators since in the end the decision about the level of the self-sufficiency target period remains a political one and is related to the question how likely a severe input disruption scenario is estimated.

$$BSS_{a,t} = S_t - L_{a,t}$$

$$L_{a,t} = \sum_{h=t}^{t+a} R_h$$

$$S_t = \text{Energy content of storage in MWh in } t$$

$$a = \text{Target self sufficiency timeframe in hours}$$
$$\text{(i.e. 168 hours for a one week self sufficiency target)}$$

$$R_t = \text{Residual load in MWh in } t$$

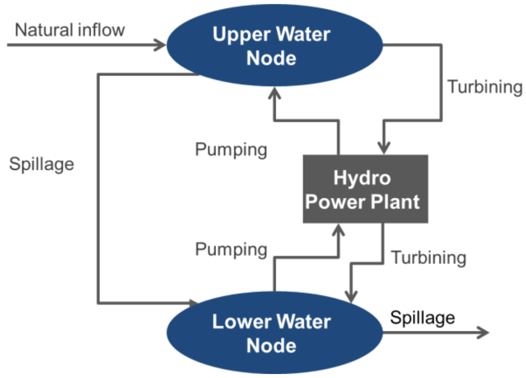
4. Numerical Analysis for the Case of Switzerland

4.1. Model

To test the indicator described in the previous section, we are using an extension of the Swissmod model described in Schlecht and Weigt (2014). The model represents the Swiss generation and transmission infrastructure as well as Swiss load in high detail. The model uses a detailed hydro structure with hydro cascades including more than 400 hydro power plants and more than 200 storage lakes. Exchange with neighbouring countries is included by aggregated generation and demand structures for France, Germany, Austria and Italy.

The model is set up as a nodal pricing model with hourly resolution and uses the DC load flow approach (see e.g. Schweppe et al. 1988, Stigler and Todem 2005, Leuthold et al. 2012 or Schlecht and Weigt 2014). The model is set up as a cost minimization problem using a quadratic cost function. A nodal balance equation including hydro generation and pumping, conventional generation, RES infeed, nodal load and line flows to and from each node ensures market clearing for every given hour. In situations of imminent system failure, load can be shed at each node, using a value of lost load of 10,000 Euros per MWh. Generation by conventional and hydro power plants as well as pumping are limited by the respective capacities. While conventional generation technologies are operated according to the market, RES are considered as exogenously defined infeeds in Swissmod. The in detail representation of Swiss hydro power is based on the HydroGIS database (Balmer 2013). Each hydro power plant in the model is connected to virtual waternodes which represent upper and lower storage lakes, rivers or penstocks that are assigned a maximum storage value representing their storage capacity. Consecutive power plants and waternodes form cascades to be able to represent the interaction of connected hydro power plants and storage lakes. Storage levels in each period t are determined by the storage level in the previous time period less water outflows plus water inflows. Water outflows occur either due to pumping by a hydro power plant above the storage or by turbining by a hydro power plant below the storage. Water inflows are defined accordingly, while natural injections are added to all upper water nodes in each cascade. Power plants are allowed to spill water to process excessive inflows (see Fig. 1).

Figure 1: Schematic hydro representation



For the Swiss neighbouring countries Germany, Austria, France and Italy conventional generation capacities, yearly demand and renewables generation are based on the EU Reference scenario 2016 (Energy Trends) by EC (2016b). Since the Energy Trends do not provide any time series data, the infeed profiles for Wind and Solar are taken from the Renewables.ninja simulation tool (Pfenninger and Staffell, 2016). Load profiles are based on data provided by the open-power-system-data platform (OPSD, 2017). Renewable infeed and load profiles are scaled to match total yearly renewables generation and load per country as given by the Energy Trends.

4.2. Scenarios

In order to demonstrate the application of the indicator as short and long term planning tool, a set of short and long term scenarios are considered in this paper. Table II gives an overview of these scenarios. For the short term analysis, a set of scenarios for the year 2020 with varying weather conditions is used. The varying weather conditions affect both demand as well as generation from hydropower, wind and solar in Switzerland and its neighbouring countries. For the long term analysis, scenarios for the years 2020 to 2035 are considered. In contrast to the short term scenarios, weather conditions are assumed to be non-varying in the long term scenarios. In total 13 scenarios are analysed.

Table II: Scenario overview

	Demand scenario			**Supply scenario**		
Year	std	min	max	std	min	max
2020	x	x	x	x	x	x
2025	x			x		
2030	x			x		
2035	x			x		

4.3. Results

4.3.1. Indicator for Hydro Rich Countries

The following section shows selected preliminary results for one scenario combination, looking at the year 2030 under non-favourable weather conditions. This scenario has been selected as it has not only shown results for the DSS and BSS indicators, but also occurrences of lost load events that are needed for most of the other indicators for system adequacy shown in section 2 to show positive values.

The DSS indicator (Fig. 2), representing the maximum duration of storage based supply in the case of import disruptions, shows a clear annual pattern. Starting a 2950 hours of DSS in October, the value slowly decreases down towards 395 hours by the end of March. This means, that under an assumed import disruption, the energy content of all Swiss hydro storages would be able to keep the system operational for the next sixteen days. Within the first five days of April, the DSS value increases significantly up to its maximum value of 5902 hours. Afterwards, the level of the DSS starts decreasing again towards its initial value at the end of the hydrological year.

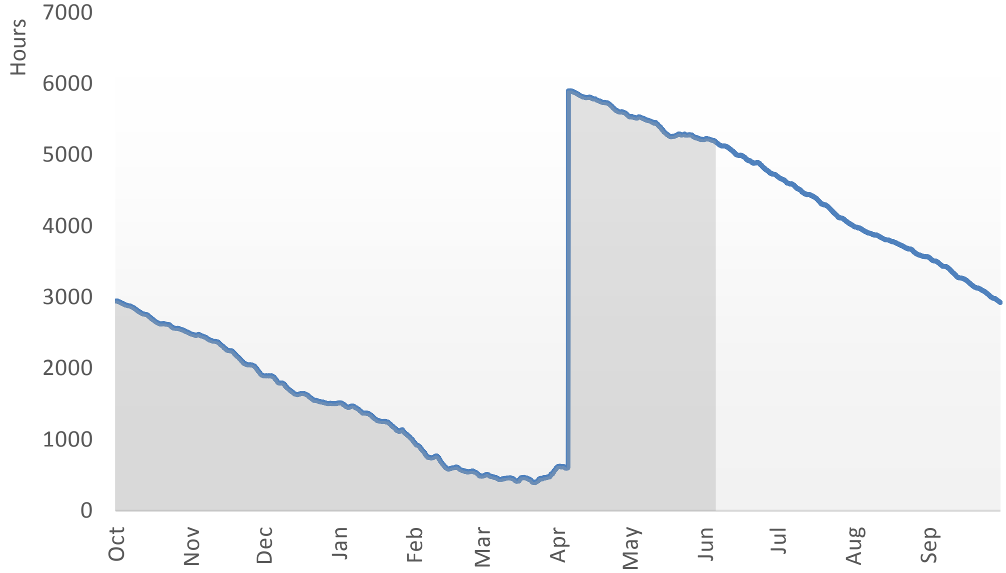


Figure 2: Duration of storage supply (DSS) results [h]

The observed annual pattern is mostly driven by a steep decrease in the energy content in swiss hydro reservoirs towards the middle of the hydrological year and the subsequent strong increase in inflows due to spring melt, replenishing the energy content of hydro reservoirs (see Fig. 3). At the same time, residual load switches from a positive value (more demand than generation) to a negative value (more generation than demand), as hydro power plants strongly increase their output, profiting from substantially higher water inflows in spring.

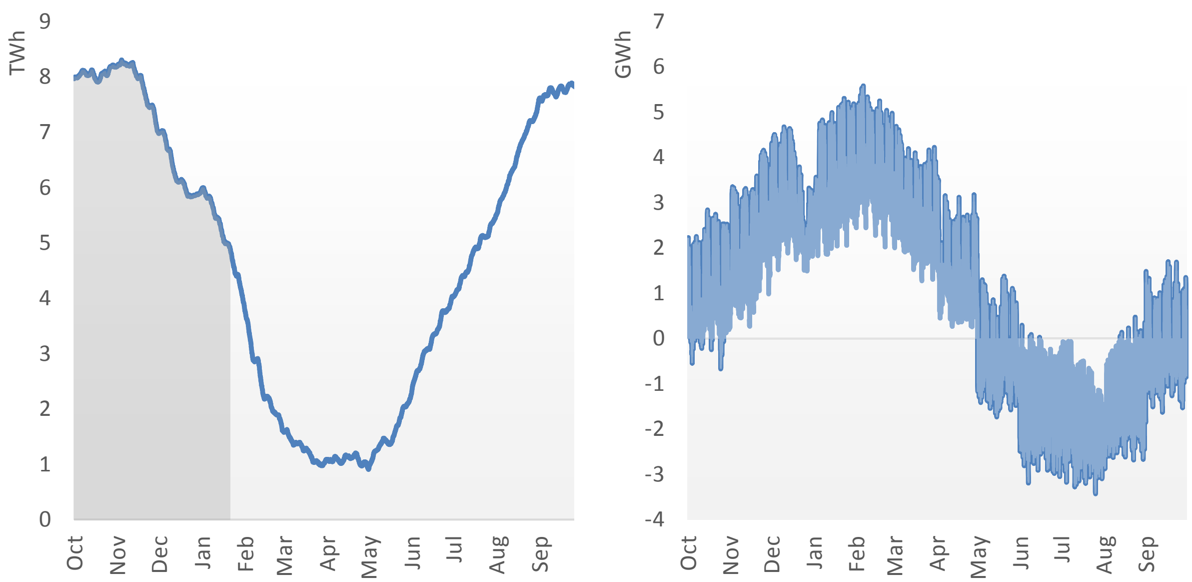


Figure 3: Storage energy content (left) and residual load (right) used for DSS calculation

The second indicator, representing the buffer of storage supply which is available (positive values) or would be required (negative values) to cover the residual load over time horizons of one week, two weeks, one month or two months shows similar seasonal patterns to the DSS, respectively the energy content results. However, the BSS exhibits no sudden jumps in its curve progression, as compared to the DSS: In the scenario presented here, only a BSS for two or one months can be found to reach a critical value below zero. This reflects the results of the DSS that at least 395 hours or more than 16 days of storage based supply in the case of import disruptions are possible at any given time. The bimonthly indicator shows a requirement for an additional buffer of storage supply from the end of January, lasting until the beginning of April. Even though the bimonthly indicator is positive throughout the rest of the year, the periods from the end of December and during April show a buffer value that is lower than 0.5 GWh. The monthly BSS becomes negative only after the middle of February and until three days after the bimonthly BSS switches to positive values. Minimum BSS values are – 1.5 GWh for the bimonthly, – 1 GWh for the monthly, 0.3 GWh for the fortnightly and 3 GWh for the weekly indicators.

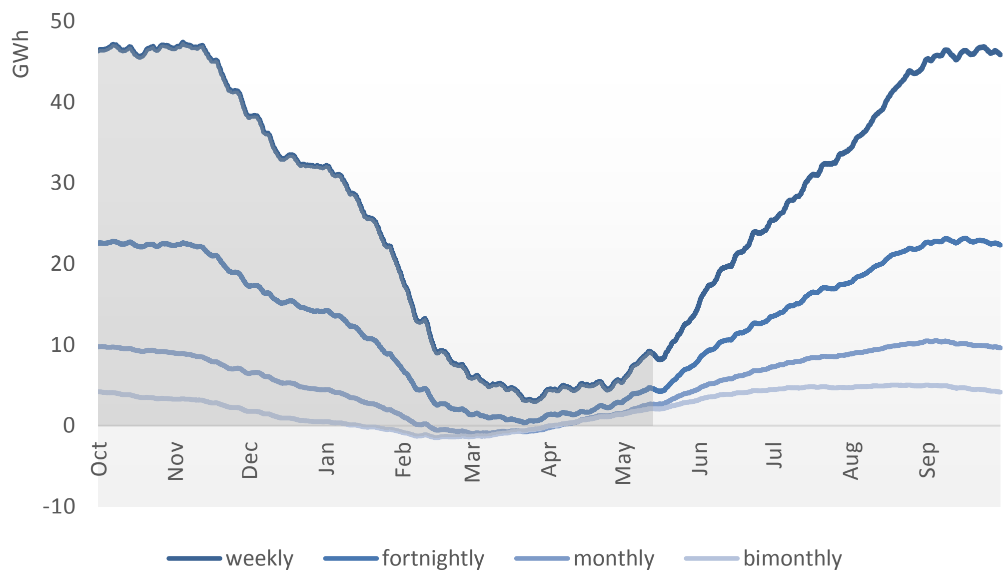


Figure 4: Buffer of storage supply (BSS) for different time horizons of import disruption [GWh]

4.3.2. Comparison to Classical Indicators

The two indicators presented here have clearly shown the contribution of storage to system adequacy and the importance of not only looking at values above or below a certain threshold, but rather considering all system states. Fig. 5 shows results for hourly loss of load, which is the basis for the calculation of EENS and LOLE for the same scenario run. Expected energy not served amounts to 10 GWh in total, occurring in 56 hours of loss of load expectation.

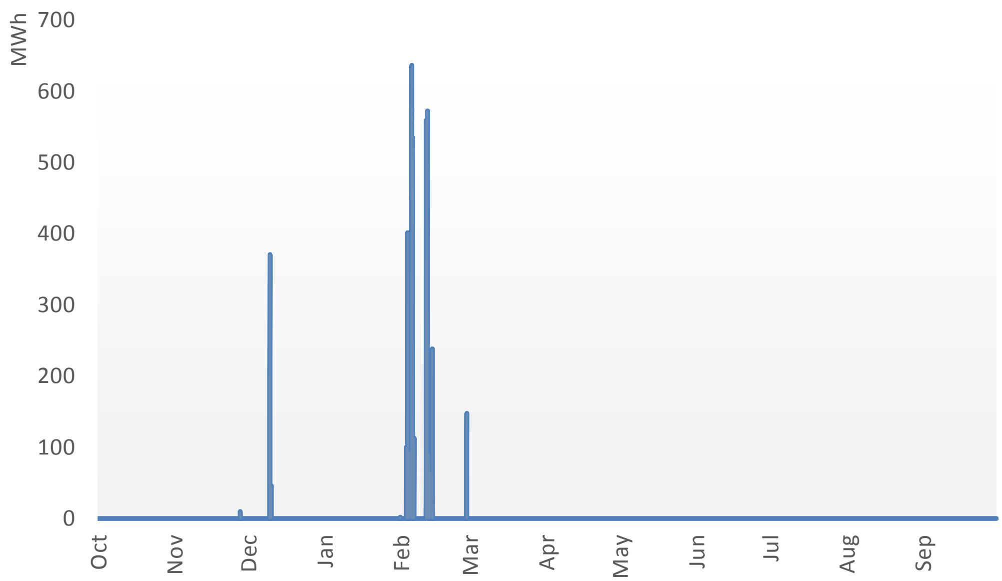


Figure 5: Hourly loss of load [MWh]

In comparison to the DSS and BSS indicators presented in section 4.3.1, several lost load events occur in December and thereby outside of the critical hours identified by the two indicators. However, the majority of lost load events coincide with the tight storage situations in February and March. At the same time, the hourly loss of load is not able to fully capture the continuity of the critical situation lasting from January until April as shown by the BSS and .in March and April as shown by the DSS.

5. Conclusion

The present paper proposes and applies two new indicators to evaluate system adequacy in hydro dominated countries. The indicators show the maximum duration of storage based supply and the buffer of storage supply which is available or would be required to cover the residual load over different predefined time horizons in the case of import disruptions. Both indicators seem to be a useful complement to more classical indicators of system adequacy. On the one hand, they are able to identify similar critical situations. On the other hand they provide additional information on the dynamics and duration of such situations and the amount of hydro generation and storage capacities needed to improve system security to a politically defined level – e.g. of one or two weeks of being able to deal with import disruptions. When analysing the results shown here, it is important to keep in mind that they represent a rather critical situation and should not be generalised towards the overall system status under varying conditions, as system adequacy in the countries that are part of Swissmod is currently at a high level according to our results for the majority of other scenarios.

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