Čepin Marko 0000-0002-6889-3592
University of Ljubljana, Ljubljana, Slovenia, marko.cepin (at) fe.uni-lj.si

Reliability of power systems with increasing contribution from wind and solar power

Keywords

reliability, power, wind, solar, renewable, energy

Abstract

Several methods, indices and measures have been developed, which highlight the questions about the power systems reliability each from its specific viewpoint. The objective is to present selected reliability measures and their application related to system generation This work is focused to adequacy methods. Emphasis is placed to two groups. One group represents distribution reliability indices, where the system average interruption frequency index and system average interruption duration index are shown in theory and in practical examples through the years in selected countries in Europe. The other group represents generating power where the improved loss of load expectation is presented. Results show distribution power system reliability indices: system average interruption frequency index and system average interruption duration index, and their comparison across countries. In addition, results show improved loss of load expectation for a power system with a variety of power plants and with sensitivity cases adding the power plants to the power system or taking them out. Specially, wind versus nuclear is emphasized. Specially, the importance of reserve power is demonstrated, where wind power contribution is increasing significantly. The results show that if more wind and solar are added to the power system instead of conventional power plants, a significant quantity of reserve power needs to be added in order not to jeopardize the power system reliability.

1. Introduction

Electric power system is one of the most complex systems, which is established by the mankind. Due to its complexity it is relatively difficult to define and assess the reliability as a single parameter of a single system. Therefore, several methods, indices and measures have been developed, which highlight the questions about the power systems reliability each from its specific viewpoint [1], [6].

The objective is to present selected reliability measures and their application related to system generation. The term adequacy can be considered versus the term reliability. Namely, reliability methods in power systems consists of two main groups: adequacy and security.

- Adequacy is related to the existence of sufficient generation of the electric power system to satisfy the consumer demand.
- Security is related to the ability of the electric power system to respond to transients and disturbances that occur in the system.

This work is focused to adequacy methods and solutions. We use the word reliability, because it is more generally known.

2. Methods

The generally accepted definition of reliability defines the reliability as the characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time.

2.1. Review of power system methods

Several methods related to reliability of power systems in terms of adequacy are collected in books [1], [6] and other references [2]–[5], [7]–[11], [13]–[16], [18]–[19]. The methods can be divided to several groups.

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One includes the methods, measures and indicators which focus to generating power and energy which is produced in power plants.

- Generation reserve margin is a measure, which shows how the capacity of power system exceeds the peak consumption [1], [6].
- Capacity margin is a different term, but has a similar meaning. The capacity margin is the proportion by which the total expected available generation exceeds the maximum expected level of electricity demand, at the time at which that demand occurs [12].
- Percent reserve evaluation is calculated by comparing the total installed generating capacity at peak with the peak load [1], [6].
- Load supply index shows the ratio between generation capacity and peak load.
- The loss of load probability is defined as the probability of the system load exceeding available generating capacity under the assumption that the peak load is considered as constant through the day [1]–[2], [6]–[8]. The loss of load probability does not really stand for a probability. It expresses statistically calculated value representing the percentage of hours or days in a certain time frame, when energy consumption cannot be covered considering the probability of losses of generating units [1]–[2], [6]–[8].
- The loss of load expectation is a similar method to loss of load probability with difference in expressing the results [1]–[2], [6]–[8]. It expresses the number of hours or days in a certain time frame (normally one year), when energy consumption cannot be covered by generation considering the probability of losses of generating units

$$LOLE = \sum_{i=1}^{ii} p_i \cdot t_i,$$

where

$$t_i = time,\ P_{load} > \sum POWER_{in-i}$$

and

i – index of considered state;
p_i – probability of state i;
t_i – duration of loss of capacity of state i, the time interval, in which the capacity of power plants in operation does not reach the power of load;
ii – the number of states

$$ii = 2^n;$$

n – number of power plants in the system;
P_{load} – power system load with its minimal value $P_{loadmin}$ and its maximal value – $P_{loadmax}$;
$POWER_{in-i}$ – the sum of powers of the power plants, which are assumed available in state i

$$p(i) = \prod_{r=1}^{n1} a(r) \cdot \prod_{s=1}^{n2} \big(1 - a(s)\big);$$

$n1$ – number of plants available for certain state;
$n2$ – number of plants unavailable for certain state;

$$n = n1 + n2$$

$a(r)$ – availability of plant r;
$a(s)$ – availability of plant s.

- Improved loss of load expectation, which is particularly applicable for consideration of power systems with large percentage of intermittent power sources such as wind and solar power. *Figure 1* shows graphical representation of parameters for determining the improved loss of load expectation. Figure shows the main difference between the loss of load expectation, where the sum if installed power ($\Sigma Power_i$) is not a constant, as it is the case for classical loss of load expectation (sum of installed power of all the power plants considered), but varies through time. Variations through time depend on the environmental factors. Wind power depends on wind speed as the main but not the only parameter for determining the wind power. Solar power depends on solar radiation as the main but not the only parameter for determining the solar power.

The other group can be considered as reliability and performance indicators of power plants. Some of them are plant specific and developed for specific plants. Some of them are more general and can be applied for different power producing plants, such has the following examples.

- Unit capability factor is defined as the ratio of the available energy generation over a given time period to the reference energy generation over the same time period expressed as a percentage.

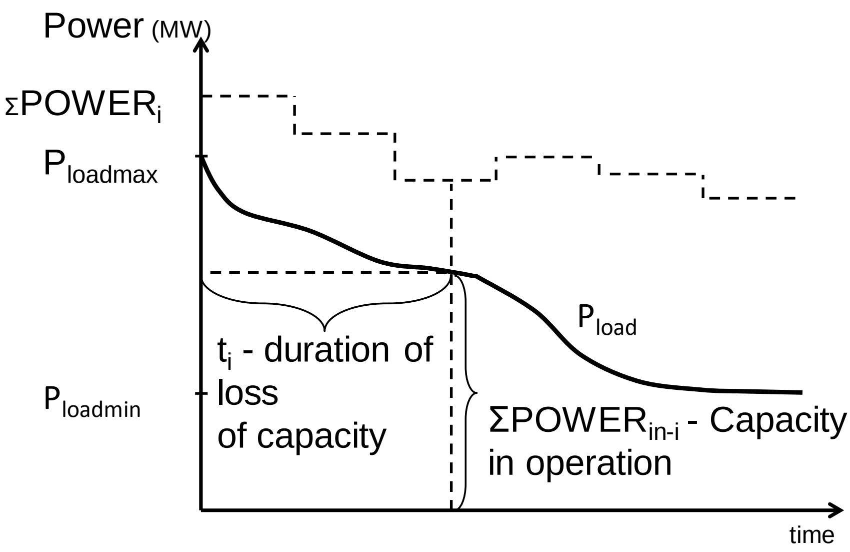

Figure 1. Graphical representation of parameters for determining improved loss of load expectation

- The unplanned capability loss factor is defined as the ratio of the unplanned energy losses during a given period of time to the reference energy generation expressed as a percentage.
- Time availability factor is defined as ratio of the unit available hours in a given period, to the total number of hours in the same period, expressed as a percentage.
- The capacity factor is the ratio of the energy produced during the given period to the energy that could have been produced at maximum capacity under continuous operation during the whole that period.
- The forced outage rate (*FOR*) is the basic generating unit parameter used in static capacity evaluation and it represents the probability of finding the unit in forced outage at some distant time in the future. It can be better defined as unit unavailability, as it is not expressed in unit of a number per time period as the rates usually are.

The next group can include distribution reliability indices. The distribution reliability indices are applicable for distribution power systems, which is the portion of power system closer to the consumers [3], [6], [13]. Only two of more than forty indicators are defined here due to the reasons of space.

- The system average interruption frequency index (*SAIFI*) indicates how often the average customer experiences a sustained interruption over a predefined period of time, usually a year.

$$SAIFI = \frac{\sum_i N_i}{N_T} \tag{1}$$

N_i – number of customers interrupted by each incident *i*,
N_T – total number of customers in the system for which the index is calculated.

- System average interruption duration index (*SAIDI*) indicates the total duration of interruption for the average customer during a predefined period of time. It is usually measured in customer minutes or customer hours of interruption.

$$SAIDI = \frac{\sum_i N_i \cdot r_i}{N_T} \tag{2}$$

r_i – restoration time for each interruption *i*.

Many data are collected for the purpose of assessing those indices. Several categories of events are considered and some of the most common categories of events include the following.

Planned event is an event, which is planned by the personnel in charge. For example, it can include maintenance activities or intentional disconnections for operability reasons.

Unplanned event is an event, where some equipment is unavailable, but this was not expected or planned.

Exceptional event is an extreme event, where exceptional weather conditions or other exceptional circumstances such as large accidents or natural disasters occur that can adversely affect the

continuity of electric power supply for longer periods of time even if they occur very rarely.
In general, in nearly every of the mentioned groups, some method can be found, which is called differently by different users or it is known under the different name in different country. Due to large number of methods, it is not possible to list them all here.

3. Analysis and results

Emphasis is placed to:

- distribution reliability indices, where the system average interruption frequency index and system average interruption duration index are shown in theory and in practical examples through the years of selected countries in Europe;
- improved loss of load expectation, where the results of selected case are shown.

3.1. Distribution reliability indices – results

Figures below show distribution power system reliability indices and their comparison across countries. One has to know that the definitions and grouping of events is somehow unique in nearly each country, so the comparisons are indicative and they should be considered with care.
Figure 2 shows *SAIDI* considering unplanned events including exceptional events. *Figure 3* shows *SAIDI* considering unplanned events without exceptional events.
Figure 4 shows *SAIFI* considering unplanned events including exceptional events.
Figure 5 shows *SAIFI* considering unplanned events without exceptional events. The results show general trend of reduction of both indices through the years, which indicates increase of power system reliability at the distribution power system level.

3.2. Improved loss of load expectation – results

Base case represents power system with classical power plants without significant power coming from intermittent power sources such as wind and solar power plants.
Figure 6 shows the calculated loss of load expectation versus time.
Average loss of load expectation is calculated as little less than 10 hours per year for the base case with a variety of power plants in the example system. The variability of hydro power plants, which represents approximately one third of installed power, causes that the loss of load expectation changes with the time due to the differences in water flow, which directs the hydro power plant power generation.
Several other cases were evaluated:

- case considering additional reliable power,
- case without nuclear power plant, which is originally included in the base case,
- 3 cases with five times more wind power compared to excluded nuclear power, each with different wind data,
- 3 cases with five times more wind power compared to excluded nuclear power and a reliable power reserve for half of the nuclear power, each with different wind data.

Table 1 shows the results of the evaluated cases, with more detailed descriptions of the changes related to considered cases, which were compared with the base case.
Results show that reliability of power system decrease notably if nuclear power is replaced with 5 times more wind power and a reliable power reserve which equals half of nuclear power.
The reliability would come to the similar as base level if 5 times wind power is installed and 90% of reserve power (compared to removed nuclear power) is added at the same time.
This is important fact for planning of future power systems with more and more intermittent power.
Those results can be compared with country projections for future.
Figure 7 shows *LOLE* projection for selected countries in Europe – part 1. For the reasons of space, the countries are presented in two figures.
Figure 8 LOLE projection for selected countries in Europe – part 2.
Both figures show a large variety of quantitative goals related with *LOLE* compared by different countries. Here, one needs to know that islands, which are not in a large extent connected with many connections with neighboring power systems (or countries with less neighbors on which the power system can count), are faced with notably higher *LOLE*. Namely, if an undesired event (e.g. interruption of power supply) occurs, more isolated areas have are less ways to deliver other power either due to less connections or due to less generation variety.
Table 2 shows review of guidelines (or requirements) regarding application of *LOLE* in specific countries [17]. No common standard exists in Europe at the moment.

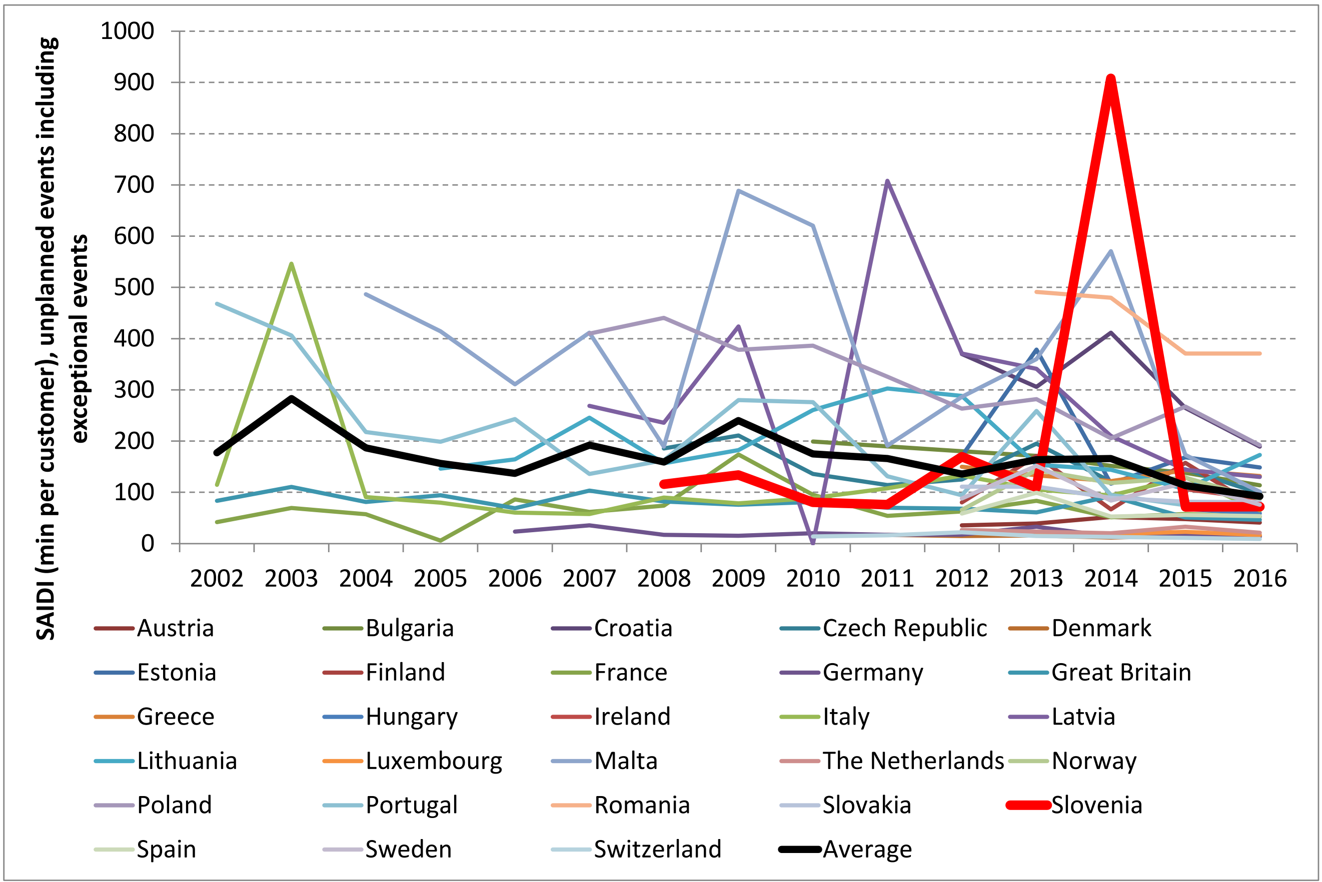

Figure 2. SAIDI – unplanned events including exceptional events

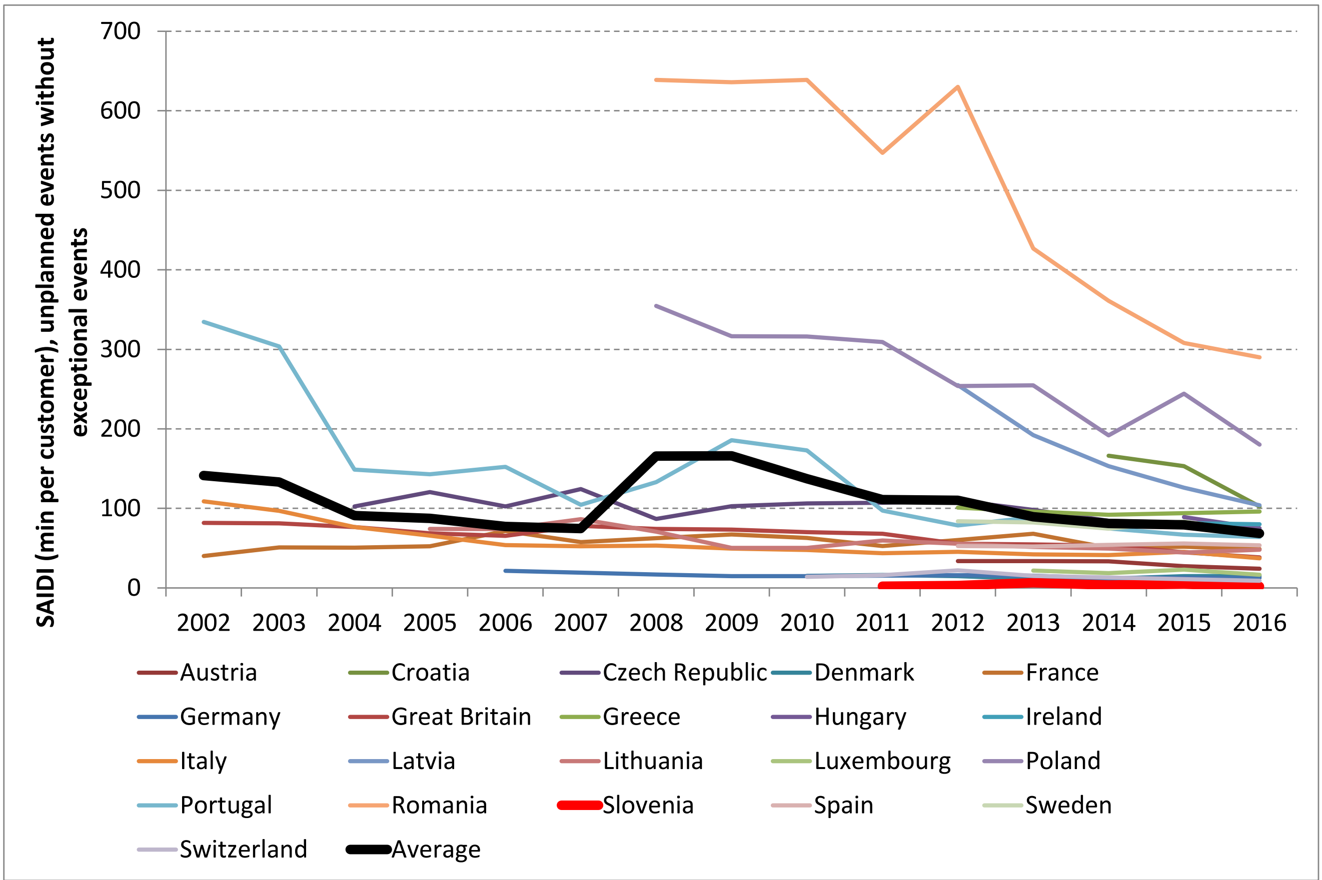

Figure 3. SAIDI – unplanned events without exceptional events

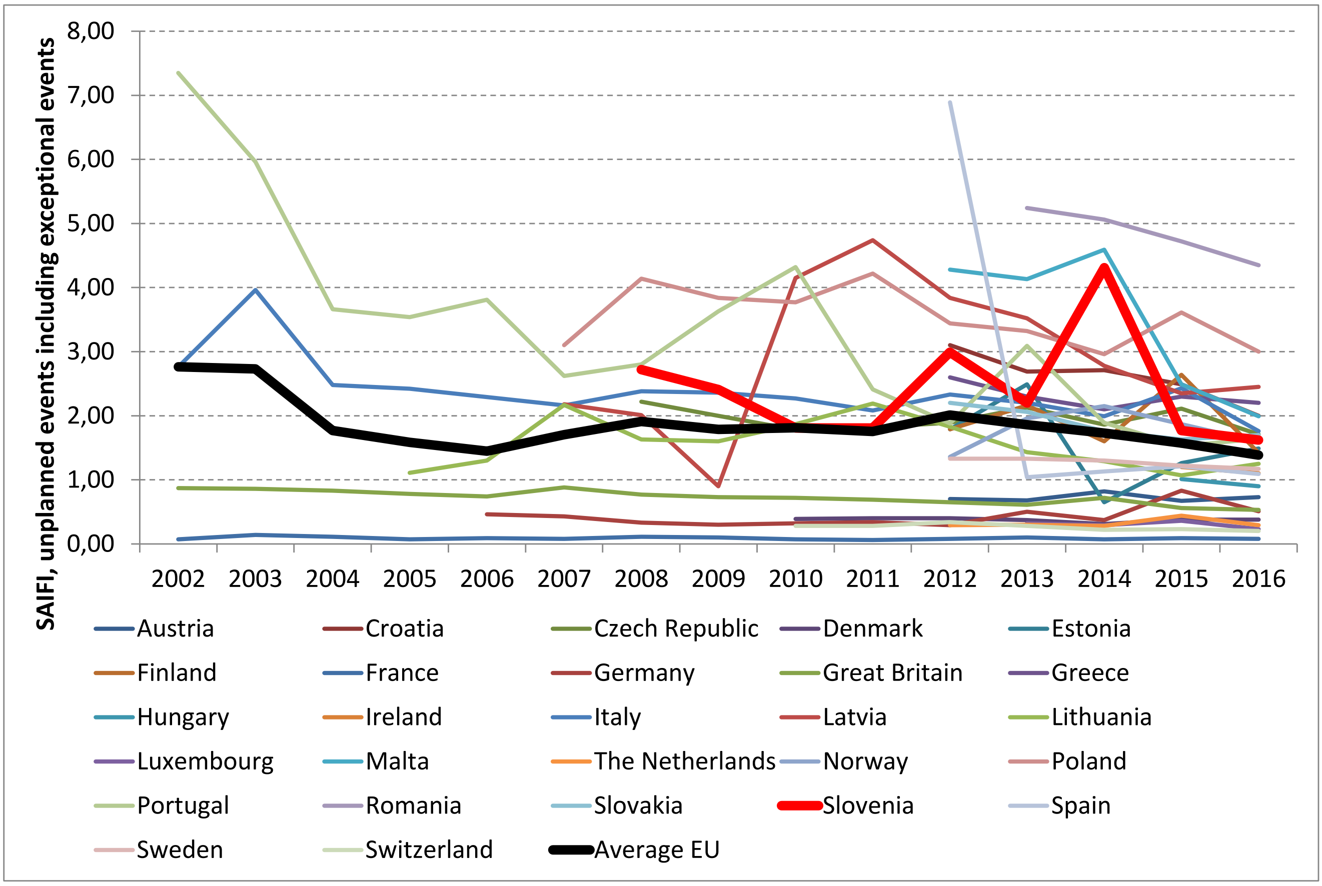

Figure 4. SAIFI – unplanned events including exceptional events

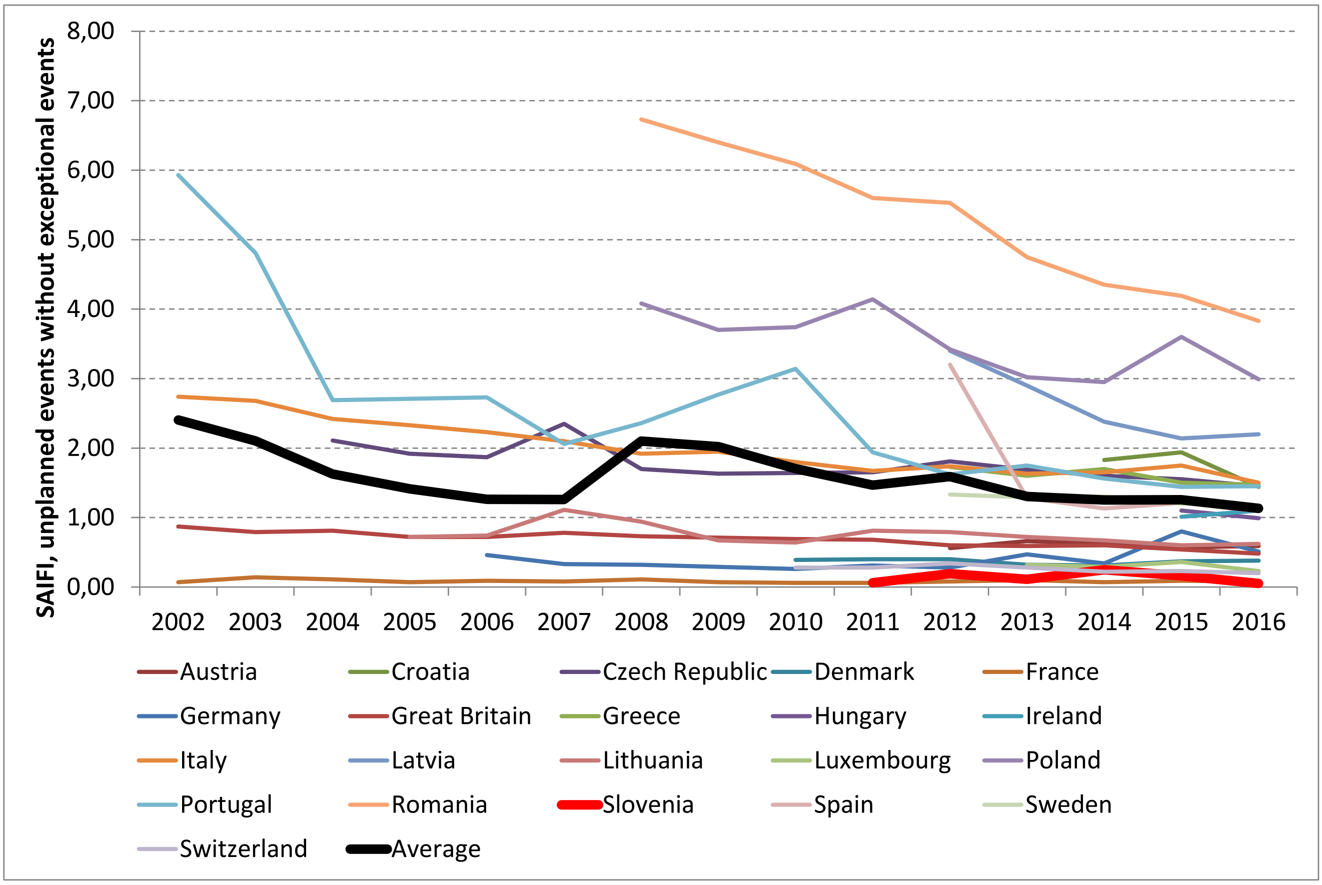

Figure 5. SAIFI – unplanned events without exceptional events

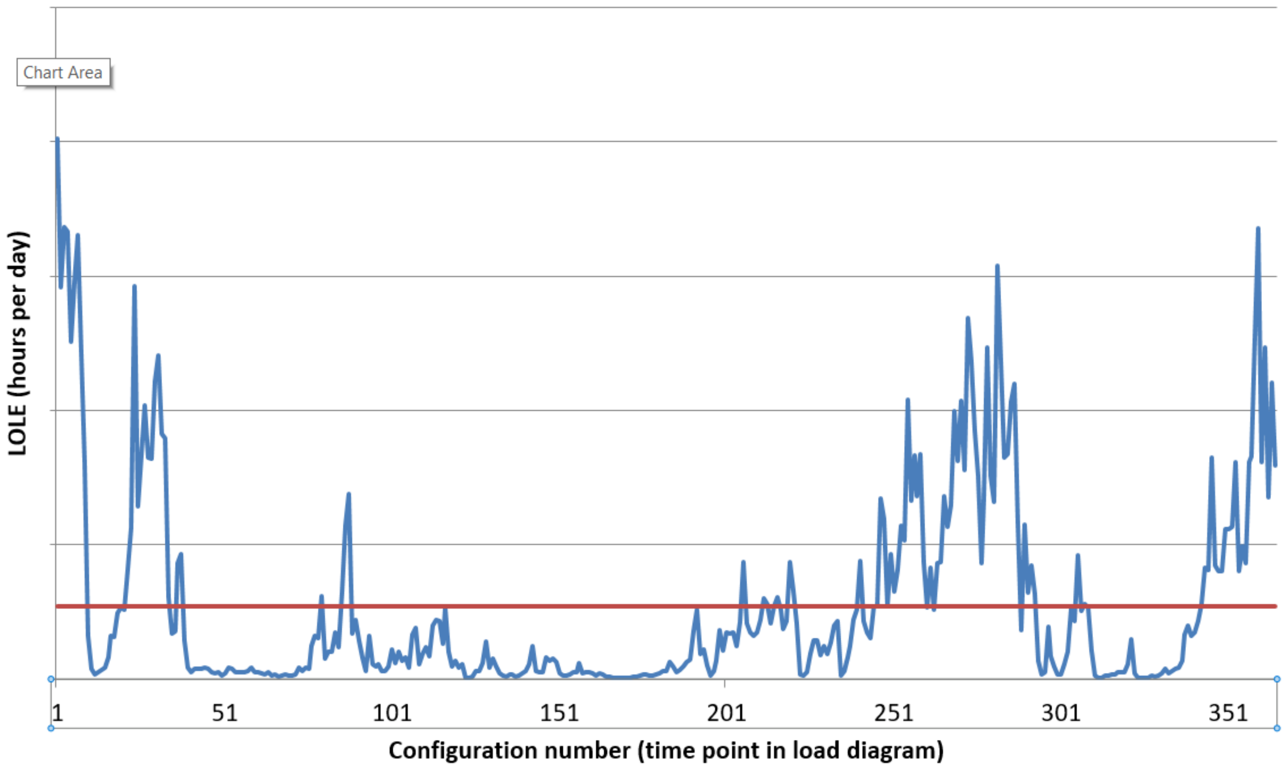

Figure 6. Loss of load expectation for base case power system (*x* axis represent days) – the curve can be represented chronologically as it is here or can be ordered by *LOLE*

Table 1. Loss of load results – summary of cases

Description of system configuration	*LOLE*
Base case (several thermal power plants including one nuclear power plants, and several hydro power plants)	9.92 hours per year
Base case and added very reliable power plant (11% of summed power of all the power plants)	0.96 hours per year
Base case but without very reliable nuclear power plant (27% of summed power of all the power plants)	419.1 hours per year
Base case minus very reliable nuclear power plant (27% of summed power of all the power plants) and with 3 wind power plants with more than 100% of additional power in wind power plants compared to summed power of all other power plants – case 1 (wind data 1)	261.9 hours per year
Base case minus very reliable nuclear power plant (27% of summed power of all the power plants) and with 3 wind power plants with more than 100% of additional power in wind power plants compared to summed power of all other power plants – case 2 (wind data 2)	199.0 hours per year
Base case minus very reliable nuclear power plant (27% of summed power of all the power plants) and with 3 wind power plants with more than 100% of additional power in wind power plants compared to summed power of all other power plants – case 3 (wind data 3)	286.3 hours per year
Base case minus very reliable nuclear power plant (27% of summed power of all the power plants) and with 2 wind power plants with nearly 100% of additional power in each wind power plant compared to summed power of all other power plants and reliable reserve power with 11% of summed power of all the power plants in the base case – case 1 (wind data 1)	47.8 hours per year
Base case minus very reliable nuclear power plant (27% of summed power of all the power plants) and with 2 wind power plants with nearly 100% of additional power in each wind power plant compared to summed power of all other power plants and reliable reserve power with 11% of summed power of all the power plants in the base case – case 2 (wind data 2)	46.7 hours per year
Base case minus very reliable nuclear power plant (27% of summed power of all the power plants) and with 2 wind power plants with nearly 100% of additional power in each wind power plant compared to summed power of all other power plants and reliable reserve power with 11% of summed power of all the power plants in the base case – case 3 (wind data 3)	46.6 hours per year

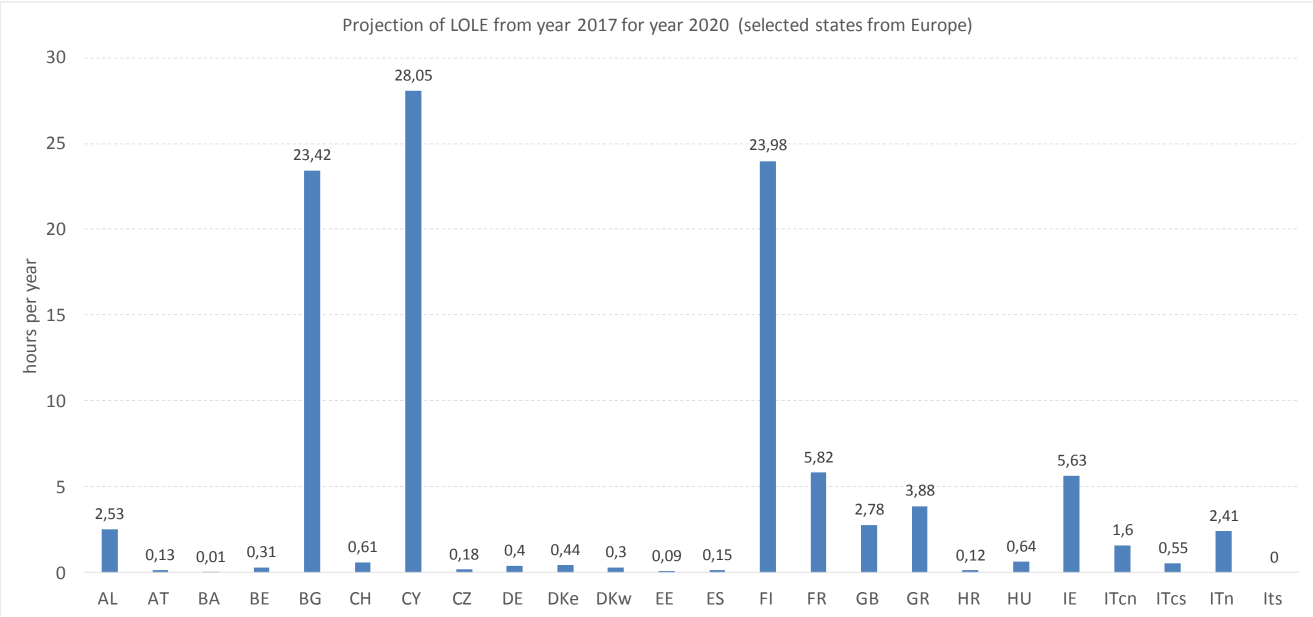

Figure 7. *LOLE* projection for selected countries in Europe – part 1

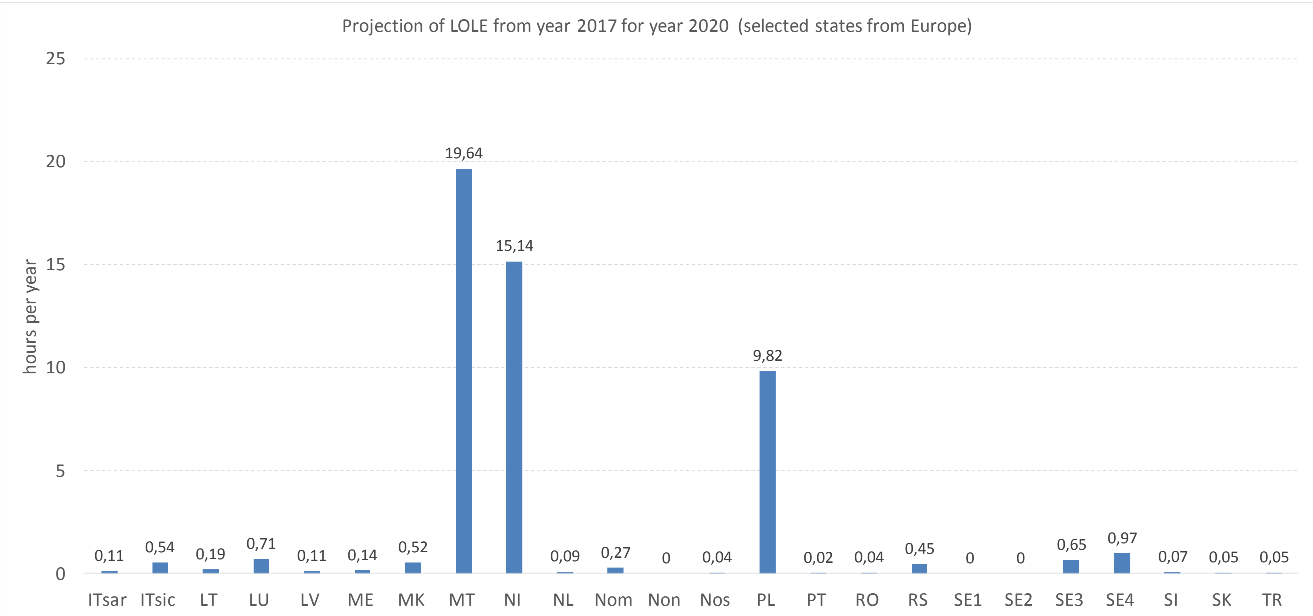

Figure 8. *LOLE* projection for selected countries in Europe – part 2

Table 2. Review of guidelines regarding application of *LOLE* in specific countries

Country	Quantitative guideline	Method
Great Britain	3 hours *LOLE* p.a.	*LOLE*
France	3 hours *LOLE* p.a.	*LOLE*
Germany	No Standard	n/a
Spain	10% reserve margin	Capacity Margin
Belgium	16 hours *LOLE* p.a. non interconnected, 3 hours *LOLE* p.a. with interconnection taken into account	*LOLE*
Ireland	8 hours *LOLE* p.a.	*LOLE*
Netherlands	4 hours *LOLE* p.a.	*LOLE*
Austria	No Standard	n/a
Bulgaria	optimal *LOLE* and amount of cold reserve	*LOLE*
Cyprus	20% reserve margin	Capacity Margin
Denmark	No standard, but the transmission system operator, which is responsible wishes to keep the Security of Supply at the current level	
Estonia	10% reserve margin	Capacity Margin
Finland	No Standard	n/a
Hungary	*LOLP* of 1%	*LOLP*
Italy	No Standard	n/a
Latvia	No Standard	Capacity Margin
Lithuania	No Standard	n/a
Luxembourg	No Standard	n/a
Malta	No Standard	n/a
Poland	No Standard	n/a
Portugal	Load Supply Index ≥1,0 with 95% exceeding probability; and *LOLE* < 8h/year (taking into account the lack of operational reserve)	Load Supply Index and *LOLE*
Romania	25% Reserve Margin (Non-standard) 10% Reserve margin (standard)	Capacity Margin
Slovakia	No standard	n/a
Slovenia	*LOLE* 8 hours p.a.	*LOLE*
Sweden	No standard	n/a

p.a. – *per annum* (per year)

4. Conclusion

Selected power system reliability methods in terms of adequacy are presented in theory and in practice.
Distribution reliability measures which are presented for selected countries in Europe, show that the reliability is improved through the years, which is shown by generally noticed trend of reduced system average interruption frequency index and reduced system average interruption duration index through the years.
Those two indices cannot show the difference with systems with more or less intermittent power sources. The efforts, which are placed by system operators to compensate the effects of intermittent power sources are not included here in those indices, similarly as the extent of intermittent power sources in the system has not been included in those indices directly.
In addition, the improved loss of load expectation is presented for selected cases. This method is more appropriate for considering reliability in terms of planning. The results show that replacing classical power with intermittent power reduces the reliability of the system (i.e. increasing the average loss of load expectation).
Moreover, the results show that reliability of power system decrease especially if nuclear power is replaced with 5 times more wind power and a reliable power reserve which equals half of nuclear power.

Reliability would come to the similar as base level if 5 times wind power is installed and 90% of reserve power (compared to removed nuclear power) is added at the same time.

So, to keep the power system reliability at desired level or to improve it, the system operators need to add to the power system not only intermittent sources but also other devices such as the more reserve power, which is not intermittent or more power storage devices.

Evaluations of case studies can be compared with projections of European countries regarding loss of load expectation and with the related country requirements, which have been established to evaluate and improve power system reliability.

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