Operational Experience of Extreme Wind Penetrations

Ana Estanqueiro, Carlos B. Mateus and Rui Pestana

Abstract — **This paper reports the operational experience from the Portuguese Power System during the 2009/2010 winter months when record wind penetrations were observed: the instantaneous wind power penetration peaked at 70% of consumption during no-load periods and the wind energy accounted for more than 50% of the energy consumed for a large period. The regulation measures taken by the TSO are presented in the paper, together with the additional reserves operated for added system security. Information on the overall power system behavior under such extreme long-term wind power penetrations will also be addressed.**

***Index Terms*—wind penetration, power reserve, system operation.**

I. Introduction

THE Portuguese power system reached 15% annual wind energy penetration during 2009. The country has not only the second largest wind penetration in the world (only overcome by Denmark), but also a very high run-of-the-river hydro capacity installed, both non-dispatchable and highly variable power sources. Thus, the limit for the large integration of wind generation in this power system only interconnected to its geographical neighbor, Spain – and, moreover, the design constraint parameter of the Portuguese power system - is the expected excess of renewable generation during the no-load periods in winter wet windy days. The planning studies carried on so far indicated that such a "windy wet winter day" would occur when the wind capacity installed overcomes 5000 MW, that maintaining the existing run-of-the river capacity - what would never occur before 2011, and more likely only in 2015 when that wind capacity goal is reached.

The Portuguese Transmission System Operator REN – Rede Eléctrica Nacional, S.A. has, so far, taken most of the possible measures to mitigate the operational impact of the planned very high wind penetration in this country, that will reach 25% in 2015, namely the planning of new transmission lines dedicated to wind power, the installation of phase shift transformers, the aggregation of wind power plants in clusters with monitoring and power control capability connected to the TSO control center, as well as defining new regulations that require all new wind capacity to have improved behavior regarding fault ride through and added reactive compensation capabilities. It was, nevertheless, a surprise to witness the occurrences of the 2009/2010 stormy winter when the non-dispatchable power generation (mainly wind and run-of the river) overcame the no-load power during several weeks, with a wind capacity of (only!) 3500 MW installed.

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II. The Portuguese Power System

The Portuguese power system has always historically had a high contribution of hydro from the fifties to the seventies of last century. However, the consumption growth and the latest investment mainly in thermo power stations (especially in natural gas), had the inevitable consequence of a strong reduction in the hydro, and renewable energy sources (RES) participation in the energy mix. Lately, a globally favorable legislation and regulation – driven by the European Comission Directives [1, 2] - lead to a marked increase in the installed capacity of wind, that turn these renewable power plants as dominant both in energy contribution and installed capacity (see Table I).

A. Main characteristics

By the end of 2009, this power system had 16738 MW installed, 4578 MW of the capacity being hydro power stations and 6690 MW thermo plants. A distinctive characteristic of the system, from its early days, is the high percentage of run of the river hydro plants (2900 MW). In the late eighties, new legislation to incentive the deployment of RES [3] was published, but surprisingly, favored the installation of cogeneration units – that reached 1631 MW in 2009 - and some micro hydro power plants (405 MW). Due to market factors, and with the exception of a small plant, wind parks were not installed till the beginning of the nineties.

In the same period (1985 to 1995) the country promoted the installation of infrastructures for natural gas distribution, and several thermo units - that traditionally were run with fuel - started to be operated with this newly available, low-emission primary source of energy. Some very small diesel units were maintained operational only for critical occurrences, being in decommissioning phase since the beginning of 2009.

Actually, as presented in Table II, more than 50% of the installed capacity is from RES. It should be noted that, from this capacity, a large amount (wind and run of the river), has reduced or no power regulation capabilities. Adding to these, all of the so-called “independent producers”, especially the large amount of co-generation - are not regulated, what gives a total value of 5470 MW (33%).

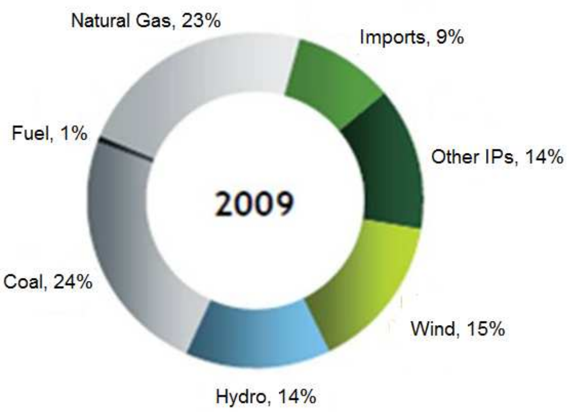
TABLE I
INSTALLED CAPACITY (DECEMBER 2009)

Capacity	[MW]
Total	**16738**
Hydro power stations	**4578**
Thermo power station	**6690**
Coal	1776
Fuel	1476
Fuel/Natural Gas	236
Gasoil	165
Natural Gas	3036
Independent producers	**5470**
Thermo/cogeneration	1631
Small hydro	405
WIND POWER	**3535**
PV	75
Wave Power	2

TABLE II
RENEWABLE CAPACITY (DECEMBER 2009)

RES Capacity	MW
Large hydro	4578
Mini/micro hydro	416
WIND	**3535**
Solar	82
Biogas	20
Biomass	92
Cogeneration	124
Wave power	2
RSU	90
Total	**8939 (51%)**

During 2009, the electric energy consumption had the first registered reduction of 2%, and totaled 49.9 TWh. From these, 7.5 TWh (15%) [4] came from wind (see Fig. 1). Although the yearly consumption was reduced, the load registered a peak during the cold harsh winter of 9217 MW



Source: REN

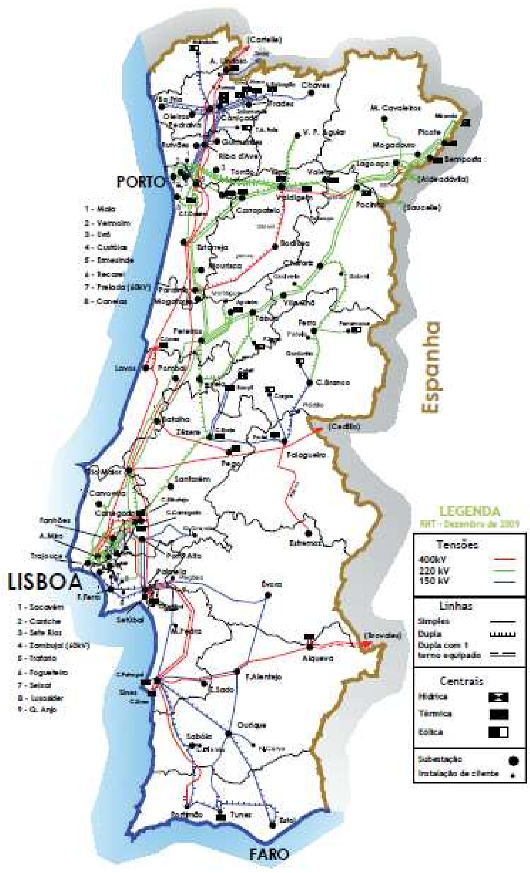
Figure 1: Energy mix of the Portuguese system during 2009.

B. The Portuguese Power System innovative characteristics

The Portuguese Power has a high degree of flexibility, mainly due to its hydro basis, and the representative reversible power capacity. These favorable conditions for high wind integration were further enhanced by a system design, in the latest decade, specifically oriented for the integration and management of time-dependent renewable RES (see [5] to [13]).

Some innovative characteristics of the Power System and the wind power plants in Portugal should be highlighted:

- Management of wind parks by clusters (“local wind power dispatch centers”) – already in use in Spain and Portugal;
- Active voltage regulation through additional variable reactive power control: e.g. tg ϕ within [-0.2, +0.2];
- Curtailment of wind production for forecasted no-load periods (recent contracts);
- Participation in the primary frequency control (5% of P);
- LVRTF – Low voltage *ride through fault* capability is requested in wind plants connected after 2007;
- Solutions for “Wind/RES energy storage”, e.g. in pumping stations, when available and cost-effective are in operation. Electric vehicles are being introduced;
- Phase shift transformers are already operating in selected substations;
- The main transmission lines (see Fig. 2) are manage by dynamic ratings and monitored for temperature.



Source: REN

Figure 2: Transmission system.

C. The RES integration design constraints

The development plan of the renewable sector in Portugal was mainly driven by the European Directive on RES (EC/70/2001) and the ratification of the Kyoto Protocol. The first Governmental decision was based on the RCM 63/2003 and defined the installation of 3750 MW of wind power till 2010. This decision was later revised by RCM 169/2005 and the wind goal was upgraded to 5100 MW. With these high goals, it became clear for the national planners that such a high penetration, in a country located in the western extreme of Europe, and only interconnected to Spain, needed added flexibility of the power system to manage critical situations of high renewable generation.

Adding to that necessity, Portugal had still high unexploited hydro resources that were disregarded for several decades, due to large popular contestation of some hydro projects located in sensitive areas. In September of 2007, the Portuguese Government published the "National Plan for Power Stations of High Hydro Potential (PNBEPH, [14])" that identified an available potential of 2055 MW new hydro plants with reduced and moderated environmental impact.

The deterministic parameters of the PNBEPH plan for the "large renewables" in Portugal (hydro and wind) were a wet windy that would occur in 2011 after the installation of 5700 MW of wind power (5100 MW from the RCM 169/05 plus 600 MW of PPAs). The study identified the power system development constraints in Portugal as the excess of renewable generation (wind + run-of-river hydro) during the no-load hours and pointed out the necessity to provide added flexibility, e.g. through energy storage, after 2011 (see Figure 3).

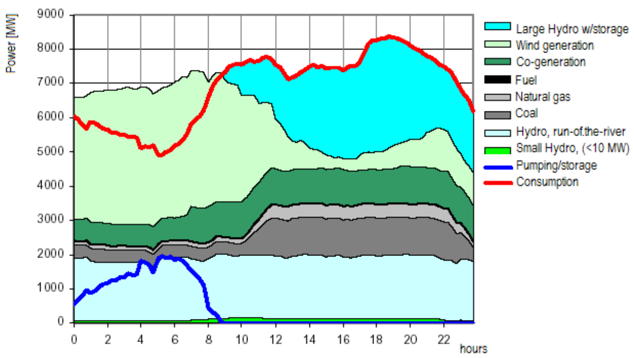


Figura 3: The scenario of generation profile for a wet windy day in 2011

The plan defined ten hydroelectric power plants for deployment/upgrading totaling approximately 1100 MW and having an estimated yearly production of 1630 GWh/year, having seven of them potential for reversible capability with a capacity of 807 MW.

Several of the hydro projects studied consisted on modernizations of old hydroelectric power plants built in the fifties and sixties of last century. Thus it was possible to start the project of the upgrading and the construction phase in a short time. These upgraded plants had a total capacity of 1140 MW, being of notice that this first phase already anticipated two reversible groups to support the existing high wind penetration that had a pumping equivalent capacity of 220 MW to be available in 2011 and to articulate directly (and bilaterally) with wind parks through DSO/wind cluster management.

III. EXTREME PENETRATIONS OF WIND POWER

Although the 2009/2010 winter was particularly windy since the autumn and rainy since the beginning of December, in its beginning nothing would indicate that the penetration of renewable sources (specially the non-regulated ones) would be different from previous winters. Moreover, the design scenarios of the PNBEPH maximum renewable penetration plan had a premise of 5700 MW wind power installed and a maximum instantaneous injection of 4500 MW – therefore, by the end of 2009, with only about 3.5 GW of wind in operation, the system was far from the study parameters.

Notwithstanding that, the severity of the winter, that had extreme wind of large return periods blowing in the whole territory, and the simultaneously occurrence of one of the wetter winters of the latest decades lead to rise the renewable generation over all anticipated limits and sweep away the deterministic premises of the hydrologic plan.

The power system operation may be divided in three sub-periods. A) Initially, in the beginning of winter , when the wind was blowing at its highest regimen, but the heavy rainy season had yet to come: B) when the heavy rain start to be felt at the run-of-the river power stations, and these started to add to wind power, with large amounts of (almost) non-regulated power: C) By the end of winter, when all dams were full, and practically there was no further energy storage capacity, but the strong wind and the heavy rain continue to be felt.

A. The early winter days

The daily profiles shown in the Figures 4 to 6 illustrate this beginning of the cold season, with wind power records in the first two weeks of November: Wind peak production and highest daily production so far at the 7th ; the highest percentage of daily consumption by wind at the 8th ; maximum instantaneous wind penetration (70%) at 15th

B. The mid-winter

The mid winter days illustrated in Figures 7 to 10 occur between Christmas and just after New Year's. The RES contribution was overwhelming during several days from Christmas to New Years: as an example, at the 29th of .December.2009, during no-load hours ~3500 MW out of 4500 MW were non-dispatchable!

C. The end of the winter

By the end of the winter – that may be strong, but it is relatively short in Portugal with the cold temperatures and stormy windy weather ending by the end of March - i.e., from mid February to the end of March, the energy mix was based almost exclusively on RES. A typical daily profile for this period in shown in Figure 11, being observable in this Figure that during the no-load hours (from 0 to 6 am) of the 25th of March 2010, the system operated with a very low reserve margin.

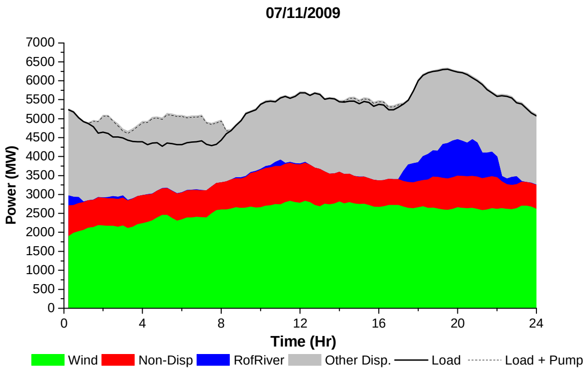


Figure 4: Load and generation profiles for 7/11/2009

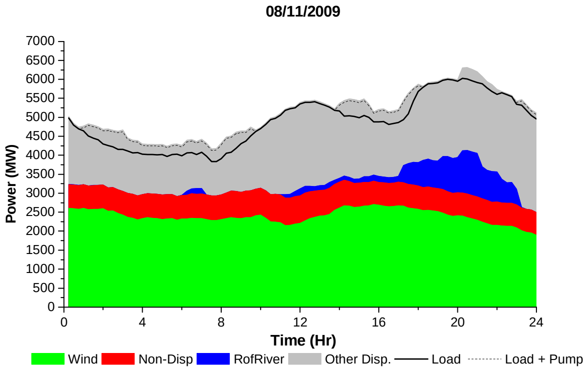


Figure 5: Load and generation profiles for 8/11/2009.

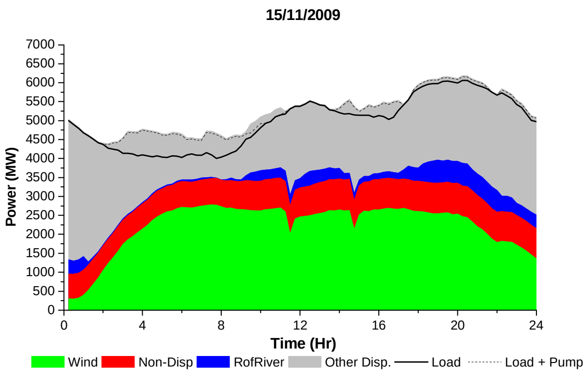


Figure 6: Load and generation profiles for 15/11/2009.

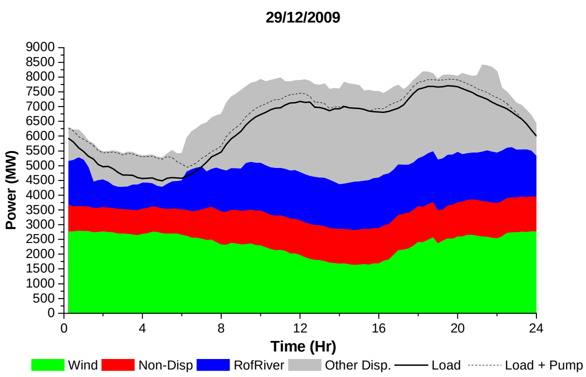


Figure 7: Load and generation profiles for 29/12/2009

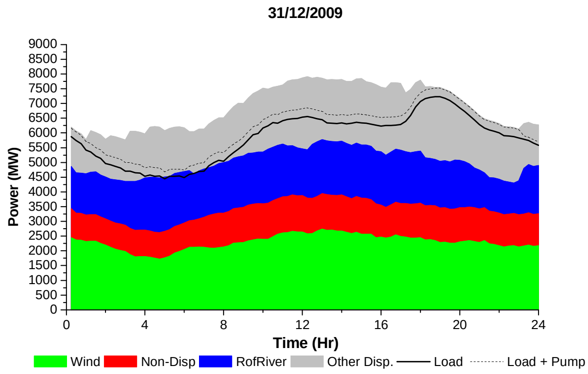


Figure 8: Load and generation profiles for 31/12/2009.

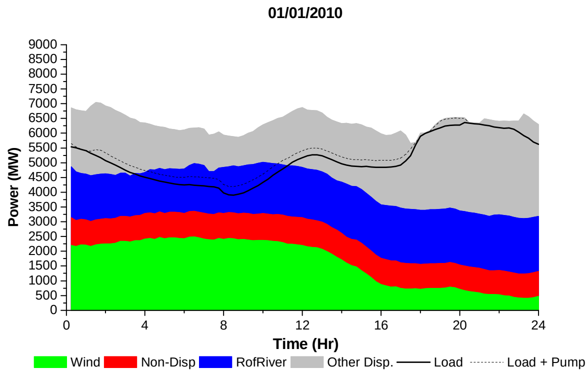


Figure 9: Load and generation profiles for 1/01/2010.

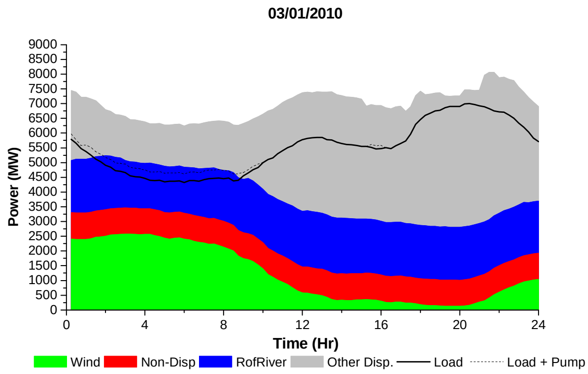


Figure 10: Load and generation profiles for 3/01/2010.

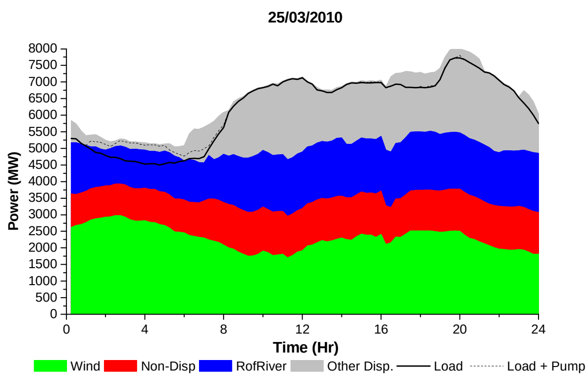


Figure 11: Load and generation profiles for 25/03/2010.

IV. Data Analysis

A. Technical operation

During the month of November (Fig. 4 to 6) the system mix had the usual contribution of dispatchable sources, mainly thermo power plants and hydro (grey), co-generation and small independent producers (in red), wind power (green) and still a small contribution of the run of the river plants (blue).

Due to the high wind regimes, in November it is already visible an excess of generation during the no-load hours, that is managed through the operation of reversible hydro power stations with pumping capacity. With the exception of a small period in the 15th of November, the pumping capacity was enough to absorb all generation. In November, 15th was the system showed the highest contribution of the wind generation to the full demand (see Table III).

The high contribution of the wind run continue over the winter, but the participation of the run of the river power plants started to show a steady increase to extreme values with the evolution of the stormy rainy winter (Fig. 7 to 10). In the 1st of January, an holiday, the demand showed a very low value while the wind and run of the river plants were peaking, and the system had the absolute maximum penetration of 117% of non-regulated power plants... It is of note that during the no-load period of the 3rd of January, no pumping capacity was used (or available) in the reversible hydro plants, due to the technical and safety limitations due to too high water levels.

February presented similar statistics and in March 25th (Fig. 11) the maximum absolute wind power delivered to the system was reached: 2978 MW – 84% of the installed capacity.

Table III
Extreme Penetrations of Wind and Non-Regulated Generation in The 2009/10 Winter

	Day	Minimum Load [MW]	Minimum Load & Pumping [MW]	Maximum Wind Power [MW]	Maximum Non-regulated Power [MW]	Maximum Wind Penetration [%]	Maximum Penetration (incl. pump.) Non-reg. P [%]
November	7.Nov.09	4277	4614	2825	4451	63%	73%
	8.Nov.09	3831	4132	2807	4129	66%	72%
	15.Nov.09	***3708***	4365	2785	3958	***70%***	78%
December	29.Dec.09	4486	4938	2786	5615	50%	97 %
	30.Dec.09	4472	4802	2836	5493	51%	100 %
	31.Dec.09	4448	4679	2745	***5773***	48%	99%
January	1.Jan.10	3900	4188	2488	5020	50%	***117%***
	3.Jan.10	4321	4608	2579	5233	49%	106%
	4.Jan.10	***4370***	***4370***	2287	5432	42%	101%
March	14.Mar.10	4178	4364	2002	4596	44%	103%
	25.Mar.10	4502	4770	***2978***	5516	54%	103%
	30.Mar.10	4610	5159	2959	5493	54%	99%

B. Market adequacy

Some years ago, Portugal and Spain signed an official agreement, reviewed several times, to operate a single Iberian energy market, named MIBEL. Due to the intrinsic differences of the two countries energy systems, the negotiations have been long and difficult and its full implementation did not start until a couple of years ago.

Being the MIBEL still at its infancy, it is understandable that it still doesn't cover many aspects of the market that only very recently prove to be relevant for the adequate and optimized operation of the Iberian power system. The extreme penetrations of RES presented in the previous sections are one of those.

What was observed was an energy offer (of RES) from the Portuguese sub-system to the Spanish sub-system at zero cost for almost the whole winter during no-load hours - even during periods (near Christmas) when Spain (and France) were facing a harsh cold front and experiencing peak load records.

Attempts to block import of energy and force the trade of the energy from renewables (wind, hydro and run-of-the river) were unsuccessful. The excess of offer, mainly during no-load hours, (including nuclear form France) lead to large periods of zero energy value in the Iberian market, with a consequent negative impact in the Portuguese "sub-market".

C. System operation and adequacy

The system proved to operate as planned in a adequate manner. The reserves operated were always well dimensioned and neither the Portuguese sub-system, nor the Iberian - Spain was also facing record wind penetrations, although much lower than the Portuguese – experienced any drastic occurrence due to extreme wind penetrations.

The additional reserves displayed in the Figures are necessary due to the high wind penetration verified in this period. As usual in systems with relevant wind capacity, the wind generation forecast errors originate a mismatch of load/generation that have, as a consequence an increase of the level of the reserves operated in a system [15]. In Portugal, the disconnection of wind generation due to lack of RTF, is not a major concern, once these plants reconnect in 5 minutes, less than the 15 minutes required by UCTE. This type of operation is feasible once there are not frequency regulation concerns - the main inertia comes from central Europe.

The major current problem is the lack of raping down regulation under high wind regimes as the ones that occurred in the 2009/10 winter, since during that period the wind production could not be curtailed. The options of the system operator were to increase the hydro pumping and reduce (even curtail) the import capacity. The system operator always tried to keep two thermal unit's (coal or natural gas) to keep the voltage stability on the south regions, since the main hydro and wind generation are located on the north of the country.

To export the excessive wind production was often not feasible due to the strong correlation with Spain in what concerns to the renewable generation availability, this fact being reinforced by the lack of inter-change capacity between Spain and France.

V. Conclusions

The Portuguese power system experienced an extreme wind penetration during the 2009/2010 winter, that peaked up to 70% of the instantaneous power and showed several days with a wind energy contribution above 50% and the whole winter with a wind participation in the mix above 30%.

While the Iberian market, MIBEL proved to be unsuited to deal with this amount of renewable generation, the Portuguese power system proved to be robust and fully adequate to all technical challenges introduced by the participation of non-regulated sources in the amount of 100% of the consumption.

Some regulatory consequences already emerged from the situations presented in this paper, namely the recent publication of new legislation for curtailment of wind power in Portugal. In the light of the experience gained during the past months of extremely high wind and non-regulated generation, it's natural that new procedures will be developed and tested against the recent methodologies published in the literature, (e.g. [16] to [27]).

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VII. Biographies

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