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Hydro Pumped Storage Power Plants perspectives in SEERC Region

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ABSTRACT
The paper is focusing to the hydro pumped storage power plants perspectives in SEERC region, investigating their present market position, that has clearly been jeopardized by low electricity market prices and small peak – off peak electricity market price differences. Lack of positive market signals could stop the development of new hydro pumped storage power plants projects in the region, and prevent the existing ones in achieving expected financial goals. Paper is analysing future power system operational needs in high renewable sources penetration environment, proposing a new perspectives for existing and new hydro pumped storage power plants in SEERC region.

KEYWORDS

hydro pumped storage, power system operation, renewable sources, flexibility, electricity market, energy policies, energy investments

1. INTRODUCTION

Present circumstances and situation in European countries regarding energy policies, energy investments and electricity market development are characterized by following. Recent trends in EU energy policies towards the reduction of greenhouse gas emissions and increase of the renewable energy sources (RES) share in overall energy mix are continuing to grow, with much higher requirements until 2030 comparing to 2020, and significantly higher requirements until 2050. EU energy policies have high demands towards energy sector but without a clear pathway how to achieve the set goals. Direct consequences of 2020 energy directives are already visible in the field of energy investments and electricity market.
From the EU data regarding the electricity generation installed capacity change during last fifteen years, it is crystal clear that dominant new technologies in EU energy sector today are wind and PV power plants. Gas power plants still have a high portion in overall installed capacity, but those days are already behind, because it is a known fact that some brand new gas power plants in Germany have been built and never put into the operation because of the lack of the competitiveness. Hydro power plants have a very small portion in overall EU

electricity generation installed capacity change, while technologies like coal, fuel oil and even nuclear have a negative trend, are going out of operation.

The main answer for the above described EU energy investment trends lies in the electricity market prices. Observing the electricity market prices trends in last three to four years, there is a rather stable trend of constant drop in the prices due mostly to the large penetration of RES in western European countries. Further, negative electricity market prices are occuring more and more often, coinciding with periods of extremely high RES production.

The power system operation is becoming more unpredictable than ever before in its history, demanding for more flexibility sources, that could cope with the highly intermittent RES operation unpredictability. At the same time, because of the low market prices and lack of investments in classical energy technologies such as hydro and hydro pumped storage power plants (HPSPP), due to large scale RES penetration, power system operation is facing the flexibility shortage, demanding thus for new technology opportunities such as demand side response, battery storage systems or multi-energy systems. Still, those new technologies are far from being mature, and government policies should establish an adequate framework for enabling the investments in classical power production facilities for providing flexibility.

In the second section an overview of present hydro pumped storage power plants market position, considering actual circumstances and situation over European electricity markets, with special focus to SEERC region. Third section is analysing future power system operation needs in high RES penetration environment, while in fourth section possible perspectives for existing and new hydro pumped storage power plants in SEERC region are proposed.

2. OVERVIEW OF PRESENT HYDRO PUMPED STORAGE POWER PLANTS MARKET POSITION

A typical HPSPP station is presented in Figure 1. When in generating mode, the reversible pump-turbine feeds produced power to the electric power system. Conversely, the power from an external source (e.g. grid, other plant) powers the pumps, when in pumping/storage mode. Dividing HPSPP energy output (from generation) by the energy input (for pumping regime) provides the round-trip efficiency (RTE) of the HPSPP facility. Round trip efficiency takes values lower than 1 due to overall losses. In fact, efficiency factors are applied twice, both in pumping and generating mode, and the round-trip efficiency is calculated using equation (1):

$$RTE = \frac{E_{out}}{E_{in}} \ [-] \tag{1}$$

RTE includes both hydraulic and equipment-related losses (pump, turbine, generator, motor and transformer). Typical HPSPP systems' RTE range between 65 and 80%, depending on the technical characteristics of the equipment. Older stations reflect lower RTE, while modern systems achieve RTE up to 87% [1].

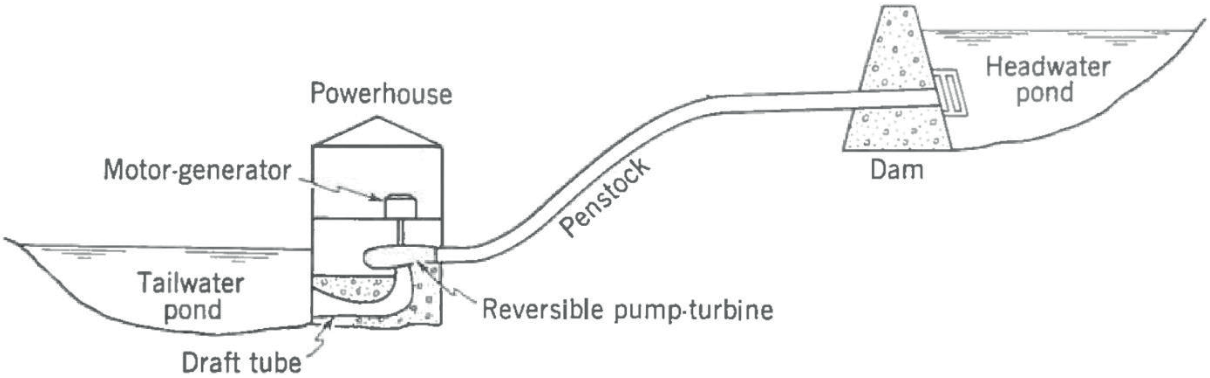

Figure 1. Pumped-hydro storage station

HPSPP systems, except for having advantageous characteristics of conventional hydropower, are readily available for peak power production with very short ramp-up time. Furthermore, in case of local or widespread black-outs HPSPP units can provide “black start” services.

HPSPP plants can generally be located far from streams and purely provide energy storage. This type of HPSPP plants are also known as pure HPSPP or “closed-loop HPSPP”. In contrast, pump-back HPSPP (also known as “mixed” HPSPP) utilizes both stored water and natural inflows to produce electricity. Apart from pure and mixed HPSPP systems, ternary HPSPP systems are a prominent technology that offers the best answer for a very fast grid response, being carried out with the torque converter which allows fast change-over between turbine and pump mode. Full regulating capability exists in both modes of operation from 0% to 100% of the unit output. As two separate hydraulic machines, the rotational direction of the motor-generator can be the same in both operational modes. This results in considerable commercial value for the power plant’s operation.

The levelized cost of electricity (LCOE) is widely used to define a characteristic cost of electricity generation. Construction costs of hydro pumped storage power plants can be shown by equation (1):

$$\mathrm{LCOE} = \frac{\mathrm{TCR \cdot FCF + FOM}}{\mathrm{CF \cdot 8766 \cdot P}} + \mathrm{VOM} \qquad (2)$$

where: LCOE levelized cost of electricity (€/MWh), TCR total captial requirement (€), FOM fixed operational and maintenance cost (€/MWh), CF capacity factor (fraction), P net power output (MW), VOM variable operational and maintenance costs (€/MWh), and 8766 (fraction) number of hours per year including leap years.
The total investment cost includes engineering, procurement and construction (EPC) costs. It also includes owner’s costs regarding the development of the project, but excludes grid connection costs. The cost of capital depends on the interest rate or on the expected rate of return on investment (ROI), the time needed for building the power plant, investment payback period and repayment of the loan. The fixed operational and maintenance cost (FOM) includes spare parts and planned maintenance, overhauls, personnel and general and administrative costs. The weighted average cost of capital (WACC) is based on a 30 : 70 ratio of equity and bank loan respectively. The cost of equity is set at 10% and the price of the loan is based on a 20 year Euro loan with a variable interest rate based on 6-month EUR Euribor plus 120 basis points of risk premium. Since the value of Euribor changes daily, our cost of capital varies over time, but on average, our WACC is 4.47%. The capacity factor is multiplied by the total number of hours in a year, (i.e. 8.766, including leap years).

Estimated costs of construction of a hydro pumped storage power plants in Croatia, with nominal power of 100 MW and with a gross drop of 750 m, is 460,000.00 € / MW. The average production cost in large hydroelectric power plants has the following structure: plant staff about 1 c€/kWh, services about 3.25 c € / kWh and various deliveries is about 0.25 c € / kWh.

In modern power systems, HPSPP capacities constitute a balancing role as net generation and load plus losses must be continuously balanced, i.e. in real time, to maintain system stability and reliability. The benefits of HPSPP units were recognized early in the development of electric power systems, especially as systems became larger and more interconnected. Roughly 75% of the overall installed HPSPP capacity in Europe is concentrated in 8 countries, with more than half of this in 4 countries: Italy, Germany, France and Spain, [2].

With increasing demand variability, HPSPP capacities utilization also increases if other balancing power units are unavailable. Usually a certain number of gas turbines perform this role in existing power systems. The extent of HPSPP plants and gas turbines usage for balancing purposes reveals the mechanisms of electricity generation portfolios managing in different European countries. The most relevant factors that influence generation portfolio management are related to ownership of the various power units, production unit efficiency, structure relation between the day-ahead market and dispatching market (monopolistic, oligopolistic markets), price setting mechanisms (marginal and priority producers), carbon pricing.

Development of HPSPP capacities is very sensitive to their utilization rate. Actually, the decreasing electricity market prices (sometimes even negative prices in the day-ahead markets are observed), stagnation of demand and new policy regimes (RES targets for 2020, 2030 and RES incentives) introduced considerable uncertainties and setbacks in future market developments not only regarding HPSPP technology but also all other power technologies. Actually, in the light of increasing share of intermittent renewable sources in modern electric power systems, one could expect that flexible HPSPP capacities would be utilized more extensively. However, when examining the HPSPP utilization rates a wide spectrum of operation levels is observed: in some countries both capacities and utilization rates increased, while in others even the existing capacities are left idle or used less than before.

Throughout Europe, the average capacity of a HPSPP plant is about 300 MW. On average, European HPSPP plants are older than 30 years and 60% of them were built between 1970. and 1990., [3]. The first large development of HPSPP capacities, occurred between 1970. and 1990. In fact, HPSPP systems were developed to utilize and store the minimum technical output of coal-fired stations as well as the night production of nuclear power plants in light loading conditions, and later on to deliver electricity in times of peak load. By the end of the 1980s only a few new HPSPP plants were constructed in Europe. Between 1990. and 2010., only 15 HPSPP plants, with a total capacity of 5.6 GW, were built in Europe.

While the need of HPSPP capacities to utilize nuclear output in EU has decreased, HPSPP importance is maintained. The increased share of intermittent RES in the energy mix should favoure HPSPP, because its technical characteristics can potentially enable higher penetration of RES (energy from wind turbines night operation used for water pumping, and curtailment minimisation). The electricity prices in Western Europe were facing a constant drop until 2016., as shown in Figure 2., as well as price difference between peak and off-peak electricity market prices [4], what was directly threatening HPSPP market position. There has been some rise due to the scarcity situation in winter 2017. Occasional occurences of negative electricity market prices could be beneficiary to HPSPP owners, but this is still not a permanent condition on which one could base its investment economic feasibility.

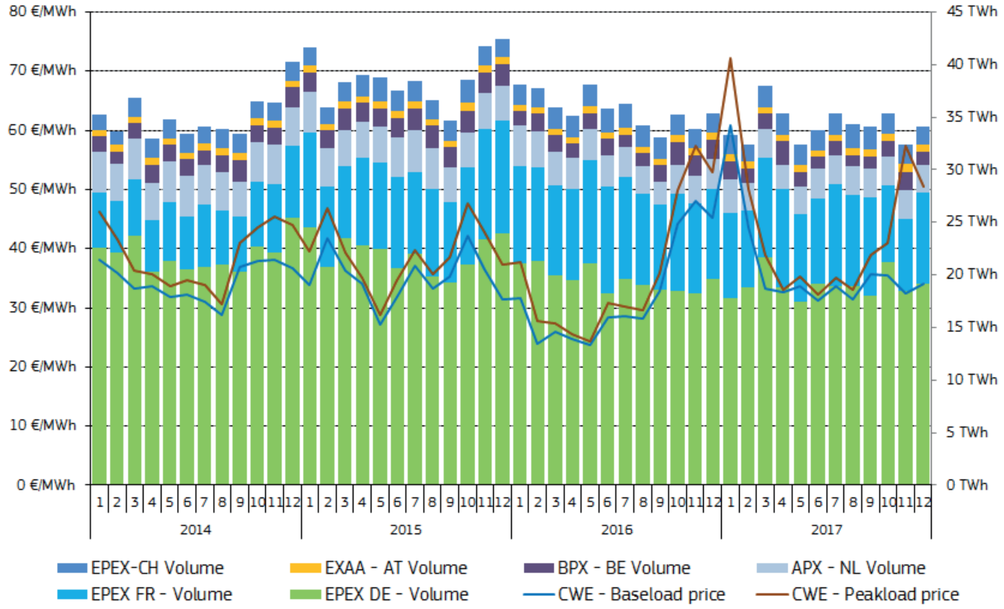

Figure 2. Monthly exchange traded volumes of day-ahead contracts and monthly average prices in Central Western Europe, source Platts, EPEX

After a long period, the market for HPSPP capacities is once again on a rising slope. In the next 10 years, more HPSPP plants will be constructed in Europe than previously in any other decade. There are plans for installing nearly 60 plants with an overall installed capacity of about 27 GW. This represents roughly 50% of the existing plants capacity and an investment of almost €26 billion. Most of the largest new plants will be constructed in countries with large penetration of wind and solar energy resources or in countries with appropriate topographical conditions (like Switzerland or Austria), [3].

In Eastern Europe the approach to HPSPP capacities is different than that in the Western European countries. Renewable wind and solar power play only a minor role. New HPSPP capacities are constructed in countries with low renewable sources e.g. Romania, Lithuania, Latvia, Estonia, Slovenia and Hungary, where HPSPP plants are mainly needed to utilize electricity from fossil and nuclear power plants. This development has been seen in the Western European countries in the period of 1970s to 1980s. The advanced economies in Poland and the Czech Republic have already undergone this phase, therefore no new HPSPP capacities are planned in these countries, [3]. Maybe the fastest and most dynamic growing market is Romania. Romanian HPSPP capacities are small, despite the favourable natural preconditions for hydropower plants. The need for new HPSPP capacities in Romania is affected by electric energy production from large fossil and nuclear power plants. Central Easte European electricity market prices [4], Figure 3., are still not so influenced by RES integration as it is a case in Western European countries.

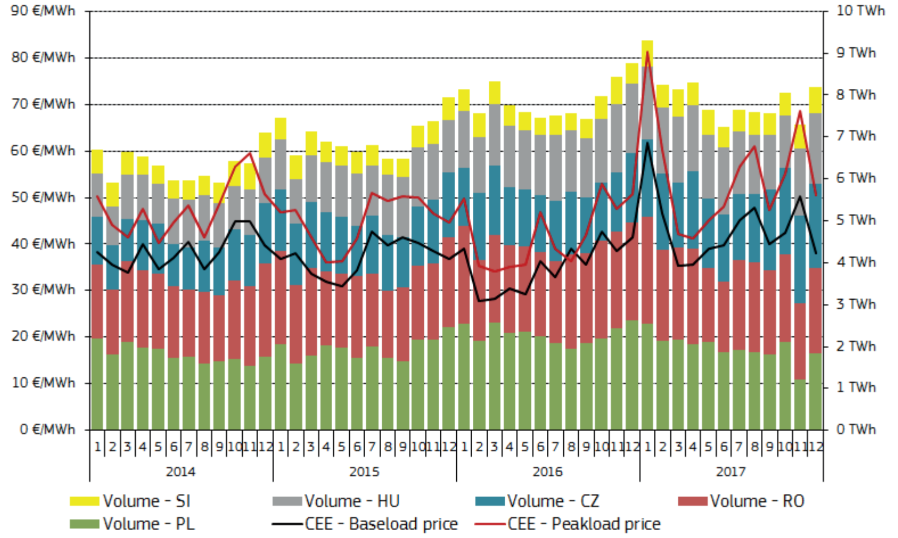

Figure 3. Monthly electricity exchange traded volumes and average day-ahead prices in Central Eastern Europe, Source: Regional power exchanges, Central and Eastern Europe (CEE)

3. POWER SYSTEM OPERATIONAL NEEDS FOR INTERMITTENT RENEWABLE ENERGY SOURCES INTEGRATION

Intermittent RES are bringing high uncertainity into the power system operation. As the generation from such kind of energy sources is in the same time hardly predictable in the day-ahead operational planning process, their operation can cause severe variations in the control area balance. Therefore, more control reserves for balancing the system are required for the secure power system operation, both in upward and downward direction.

Minimum and maximum load are important parameters considering the RES integration in certain country / control area. Those figures compared against average total RES production roughly show percentage of load expected to be covered by RES production. For the topic analysed in this article, percentage of minimum load covered by RES production is of special interest. Minimum load period occurs during night hours, and for countries with high wind power penetration, it very often coincides with periods of high wind power plants production. If there is a shortage of downward control capacities it usually leads to the curtailment of wind energy production, and thus extensive financial compensation to wind power plant owners and for redispatch.

According to [5] in European countries with large wind penetration ratio the wind curtailment is growing rapidly, both in absolute values and curtailment ratio. In Germany, the total wind generation has almost doubled from 48.883 GWh in 2011., to 87.975 GWh in 2015., while in the same period wind curtailment has grown seven times, from 410 GWh to 3.060 GWh, and with wind curtailment ratio growth from 0,8% to 3,5%. At the same time, this has caused extreme costs to the German transmission system operators. Only Tennet's total redispatch costs in Germany reached almost €1 billion in 2017.

Italy has almost similar situation, with total wind generation of 19.913 GWh in 2015. and with wind curtailment of 119 GWh. Wind curtailment ratio in Italy has droped, from 1,1% in 2013. to 0,6% in 2015., although the wind penetration ratio has risen from 5,3% in 2013. to 7,4% in 2015. Those reduction rates had happened mostly because of infrastructure upgrades linking the southern and northern Italian regions, where most of the congestions have taken place in the past, demanding for the curtailment of wind generation in southern part of Italy. Also, battery storage facilities have been put in operation in in southern part of Italy, helping the relieve of congestions.

Wind curtailment can be treated as a waste of energy, similar to the accumulation overflow in the periods of extreme hydrology. But, in the contrary to the extreme hydrology periods, which can appear at the most few times a year, the wind energy surpus can appear rather often, causing constantly repeated disturbances to normal power system operation.

It would be ideal if there would be enough storage capacities to safely store those energy surpluses and use it later, in the periods of energy shortage. This could be a double benefit for the power system operation, but also a clear benefit from the economical point of view. As the RES will continue to grow in European, but also non-European SEERC countries, the need for flexibility will be more urgent, specially need for storage capabilities.

RES integration figures in SEERC countries are quite different in integration dynamics from country to country, as well as in total amount and percentage of totally installed generation. Table 1. gives a comparison of installed generating capacity in SEERC countries, specially focusing on intermittent RES (wind, solar). Minimum and maximum loads are also compared. Observing the RES share in totally installed generation, seven SEERC countries are significantly more developed than others. Three of them, Greece, Italy and Romania, have more than 20% of RES share in totally installed generation. Austria has a significant RES share of 15,6 %, but also very high total amount of 3841 MW of installed RES generation. Turkey and Czech Republic have RES share around 10 %, but again very high total amount of installed RES generation. Than comes Ukraine with more than 900 MW, and Croatia and Hungary with more than 600 MW of installed RES generation, and moderate RES integration figures. Third group of countries consists of Slovenia, Slovakia and Macedonia, with rather low RES share, but with tendency of further development. Fourth and last group of countries are at the beginning stage of RES integration.

Table 1. Comparison of installed generating capacity in SEERC countries

Country	TPP [MW]	HPP [MW]	Wind [MW]	Solar [MW]	TOTAL RES [MW]	TOTAL GENERATION [MW]	RES [%]	Maximum Load [MW]	Minimum Load [MW]
Austria	7059	13656	2489	732	3841	24646	15,6	11728	4664
Bosnia and Herzegovina	1876	2096	0	0	0	3972	0,0	2142	868
Croatia	2005	2112	489	48	613	4730	13,0	2869	1155
Czech Republic	10735	2259	277	2027	1982	20188	9,8	10512	4446
Greece	12520	3393	2092	2605	4984	20897	23,9	9207	3314
Hungary	5611	57	328	49	681	8236	8,3	6437	2994
Italy	68867	26527	9416	19288	29384	133255	22,1	56103	18664
Kosovo	1200	72,2	0	0,6	29,82	1293	2,3	1160	240
Macedonia	1157	676	36	17	57	1890	3,0	1457	487
Montenegro	220	660	0	0	0	880	0,0	576	174
Romania	8185	6405	2965	1301	4384	20274	21,6	8752	3785
Serbia	5594	3015	0	0	0	8609	0,0	6958	2414
Slovakia	2476	2537	3	530	142	7829	1,8	4360	2285
Slovenia	1379	1296	3	270	150	3816	3,9	2144	929
Turkey	43923	26681	5751	832,5	7894	78497	10,1	44341	17796
Ukraine	27800	6200	439	458	961	55331	1,7	23898	11203
SEERC	200607	97642	24288	28158	55102,14	394343	13,97	N/A	N/A

* RES without large HPP

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4. HYDRO PUMPED STORAGE POWER PLANTS PERSPECTIVES IN SEERC REGION

Large-scale RES integration development in EU and non-EU SEERC countries will urge for higher system flexibility and energy storage possibilities. Some of the countries already have energy storage facilities, mostly hydro pumped storage power plants. Energy storage facilities in SEERC countries [6] are listed in Table 2.

Table 2. Energy storage facilities in SEERC countries

Country	Total Number	Technology Type	Rated Power (kW)
Austria	18	Pumped Hydro Storage	4680000
	1	Electro-chemical	64
Bosnia and Herzegovina	1	Pumped Hydro Storage	420000
Croatia	1	Pumped Hydro Storage	276000
Czech Republic	3	Pumped Hydro Storage	1145000
	1	Flywheel	70000
	2	Electro-chemical	40
Greece	4	Pumped Hydro Storage	1429000
	1	Electro-chemical	800
Hungary	1	Electro-chemical	500
Italy	19	Pumped Hydro Storage	7642700
	31	Electro-chemical	56178
	2	Thermal Storage	5120
	1	Hydrogen Storage	1200
Romania	1	Pumped Hydro Storage	53000
	1	Flywheel	300
Slovenia	1	Pumped Hydro Storage	185000
	1	Electro-chemical	10
Serbia	1	Pumped Hydro Storage	614000
Ukraina	3	Pumped Hydro Storage	3173000

HPSPP have a number of advantages comparing to the new energy storage technologies like battery storage systems for example. HPSPP storage capabilities are much larger, having thus the posibillity to store large amounts of energy from RES. From the economical perspective HPSPP's main advantage is peak energy production and arbitrage between peak and off-peak energy, but at the same time disadvantage are very high investment costs. Still, HPSPPs have significantly longer life cycle than battery storage systems.

HPSPP can contribute to the frequency control, but also to the system balancing and congestion relieve. Besides the system flexibility, HPSPP can also contribute to the voltage and reactive power control what is not possible for the battery systems, unless there is a combination of battery system and FACTS installed.

From the ecological perspective HPSPP's advantage comparing to the battery systems is again long life cycle, where there is no need to often replace old equipment and thus produce large amounts of waste, having issues with the waste disposal. Battery systems therefore have much higher environmental impact than HPSPPs, specially those battery systems that use nickel and cobalt, like lithium-ion batteries.

European Commission has approved six electricity capacity mechanisms so far, to ensure security of supply in Belgium, France, Germany, Greece, Italy and Poland, Figure 4. Taking into account all that was elaborated above, authors propose to establish a special kind of capacity mechanisms in SEERC, but also other countries, that would support the operation of existing and new HPSPPs, enabling that way further RES integration, and fulfillment of the ambitious EU climate goals. In further research authors will focus to the detailed elaboration of the proposed HPSPP capacity mechanism.

Figure 4. EU approved capacity mechanisms

5. CONCLUSION

Installed capacity of new RES is constantly increasing worldwide since more than 20 years, and projections foresee a continuous growth at the horizon 2040. European Union itself targets a 20% share of electricity generation by renewable energies in 2020, where wind and solar power are expected to represent the main contribution. However, these two sources of energy are known for being highly volatile and therefore, their integration in the existing power networks constitutes a challenging task. This requires development of adequate primary, secondary and tertiary production reserves and massive storage capacities where pumped storage power plants, regardless of HPSPP type should play a significant role. Because of the uncertain HPSPP future market position and economic feasibility, authors propose the establishment of a HPSPP operation support scheme through a capacity mechanism for HPSPP.

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