# Impact of the Electricity Market Prices on Energy Storage Operation during the COVID-19 Pandemic

Marin Mandić, Elis Sutlović, Tonći Modrić, Luka Stanić



***Abstract*—**With the restructuring and deregulation of the power system, storage owners, generation companies or private producers can offer their multiple services on various power markets and earn income in different types of markets, such as the day-ahead, real-time, ancillary services market, etc. During the COVID-19 pandemic, electricity prices, as well as ancillary services prices, increased significantly. The optimization of the energy storage operation was performed using a suitable model for simulating the operation of a pumped storage hydropower plant under market conditions. The objective function maximizes the income earned through energy arbitration, regulation-up, regulation-down and spinning reserve services. The optimization technique used for solving the objective function is mixed integer linear programming (MILP). In numerical examples, the pumped storage hydropower plant operation has been optimized considering the already achieved hourly electricity market prices from Nord Pool for the pre-pandemic (2019) and the pandemic (2020 and 2021) years. The impact of the electricity market prices during the COVID-19 pandemic on energy storage operation is shown through the analysis of income, operating hours, reserved capacity and consumed energy for each service. The results indicate the role of energy storage during a significant fluctuation in electricity and services prices.

***Keywords*—**Electrical market prices, electricity market, energy storage optimization, mixed integer linear programming, MILP, optimization.

## I. Introduction

In solving problems such as increasing energy consumption, large use of fossil fuels, fuel prices uncertainty and atmosphere pollution of $CO_2$, most of the countries are turned to the renewable energy sources (RES) production [1]. RES are becoming more popular, especially wind and solar [2]. However, an imbalance in supply and demand at the power system is increased due to the intermittent and fluctuating nature of the aforementioned RES [3]. One of the alternatives for solving this problem is the greater utilization of energy storage [4].

Energy storage technology has become one of the main technologies that successfully cope with the problem of higher integration of RES [5]. In addition to all storage technologies, pumped storage hydropower plant (PSHP) technology is mature and the most used storage technology suitable for bulk services and time shifting/price arbitrage applications [6]. PSHPs have a lifetime of about 50-100 years, a round-trip efficiency coefficient of about 75-85% and a rapid response to changes (in the range of seconds and minutes) [7], [8]. PSHP is widely used for regulation purposes, for a black start (grid-independent start-up) and can also participate in spinning and non-spinning reserve as well as in reactive power compensation.

Proper use of PSHPs in the power system can lead to reduced system operation costs, and due to its large storage capacity, it can affect electricity prices, enable better integration of intermittent RES in the power system and thus reduce greenhouse gas emissions [9], [10]. In the last decade, the marginal cost of producing energy became much more unstable, mainly due to the recent moves toward competitive liberalized markets. This unstable behavior of the electricity price can be benefited by using PSHP technology to capture the price differential [11]. In addition, this storage technology can also be economically viable on its own, as indicated by the trends in electricity prices in spot, day-ahead, regulating and capacity markets, which is especially emphasized in periods of energy crises (such as the crisis caused by the SARS-CoV-2).

The SARS-CoV-2 (also known as Coronavirus 2019 or COVID-19) was detected in December 2019 and it was declared from epidemic to pandemic on March 11, 2020. The pandemic has caused global economic uncertainty. Its impact on the energy sector has been quite serious. In the earlier days of COVID-19, when most economic activities were either partially or completely shut down, and while various forms of social distancing and isolation measures were in place, a high level of uncertainty emerged, affecting economic production and energy consumption [12].

In [13], the authors have analyzed several electricity markets (Germany, France, Italy Spain and Sweden) in the first wave of the COVID-19 pandemic. There has been a reduction in electricity demand and an increase in the RES energy share. In Germany, France, Italy and Spain, a significant reduction in electricity consumption was observed during the COVID-19 period compared to the same period of previous years. There was no mentioned phenomenon in Sweden because the attitude and policy of Sweden towards the COVID-19 pandemic were different from other aforementioned countries. As mentioned above, due to reduced consumption demand and increased production from RES, there was a decline in the average day-ahead electricity prices, and there were significantly more hours with negative prices compared to 2019.

The COVID-19 pandemic effects on the Iberian market economy and macroeconomic outlook have been discussed in [14]. It is also analyzed the financial status of major generating companies (primarily those affected by the COVID-19

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pandemic) as well as changes in consumption trends, production and spot market prices. The results showed that average consumption in April and May 2020 reduced by 12% and 17% compared to April and May 2017-2019. In addition to the fall in day-ahead prices, the consequence in Spain and Portugal was also a drop in the average wholesale price up to 50% and 60% in April and May. Minimum day-ahead prices reached 2 €/MWh in the observed period, and even negative prices appeared, which is a rare occurrence in the Iberian market (MIBEL). Also, the authors in [15] compared the achieved electricity (and gas) prices in Spain in the first half of 2020 with the prices predicted for that period at the end of 2019. The results show a 60% decline in electricity prices for the observed period.

In the past, there have been various globally disastrous events (world diseases, pandemics, wars, etc.) that have affected global energy consumption. Since the energy demand significantly increases after every catastrophic world event, energy demands are expected to rise dramatically in all industries around the world after the COVID-19 pandemic, as it increased after all the other catastrophic events. It is considered that the effects of the COVID-19 pandemic on the energy concept of sustainability will be significant, and RES should be the basis of maintaining that sustainability. However, the efficient harnessing of solar energy and other intermittent RES requires large-scale energy storage systems that do not disturb the electricity system balance. After the pandemic, the RES energy share is expected to grow even faster. The renewable energy system will be the fastest growing source of electricity by 2050, according to the International Energy Agency, and it will be the third largest producer of energy by 2030. The COVID-19 pandemic will only accelerate that growth [16].

Due to all the above-mentioned points, the popularity of energy storage technologies that can balance the seasonal change of energy production and consumption is predicted to increase. It is expected that research and investment in energy storage technology that will operate in combination with RES to enable the stability of the electricity grid and respond quickly to changes in energy demand, will increase significantly [16].

In this paper, the impact of the electricity market prices on energy storage operation during the COVID-19 pandemic was investigated. First, the hourly market prices fluctuations on the day-ahead market and the regulating market during the COVID-19 pandemic were statistically analyzed. Then, the operation and income generated by PSHP, which participates in several power markets, practices energy arbitration and offers services such as regulation-up, regulation-down and spinning reserve were modeled. Considering the achieved hourly power prices before and during pandemic, the optimal annual PSHP operation modes under market conditions for 2019, 2020 and 2021 were calculated in numerical examples. Finally, with regard to different annual incomes and investments, payback periods were calculated.

## II. Model

The model for calculating PSHP optimal operation mode based on income maximization was used [17]. The objective function (1) is income maximization (based on the PSHP daily operating cycle) considering energy arbitration and several services in the electricity market. The model also includes equations and inequalities as well as constraints on decision variables (upper and lower limits) as described in detail in [17]. The optimization technique used for solving the objective function is MILP.

$$\begin{aligned}\text{Max}\quad & \sum_{n=1}^{N}\sum_{t=1}^{24} h_{n,t,1}\cdot c_{n,t,1}+\sum_{n=1}^{N}\sum_{t=1}^{24} h_{n,t,2}\cdot c_{n,t,2} \\ & +\sum_{n=1}^{N}\sum_{t=1}^{24} h_{n,t,3}\cdot c_{n,t,3}+v_1\cdot\sum_{n=1}^{N}\sum_{t=1}^{24}\eta\cdot h_{n,t,1}\cdot c^{e}_{n,t,1} \\ & -v_2\cdot\sum_{n=1}^{N}\sum_{t=1}^{24}\eta\cdot h_{n,t,2}\cdot c^{e}_{n,t,2}+v_3\cdot\sum_{n=1}^{N}\sum_{t=1}^{24}\eta\cdot h_{n,t,3}\cdot c^{e}_{n,t,3} \\ & +\sum_{n=1}^{N}\sum_{t=1}^{24}\eta\cdot h_{n,t,4}\cdot c^{e}_{n,t,4}-\sum_{n=1}^{N}\sum_{t=1}^{24} p_{n,t}\cdot cp_{n,t}\end{aligned} \tag{1}$$

The variables $h_{n,t,1}$, $h_{n,t,2}$, $h_{n,t,3}$ denote offered capacities for regulation-up, regulation-down and spinning reserve services in $n^{th}$ day and $t^{th}$ hour, while $h_{n,t,4}$ and $p_{n,t}$ denote energy for selling and energy for purchase in $n^{th}$ day and $t^{th}$ hour. The prices for regulation-up, regulation-down and spinning reserve services are denoted with $c_{n,t,1}$, $c_{n,t,2}$, $c_{n,t,3}$, while the electricity prices for executed services as well as for selling (in turbine mode) and purchasing (in pump mode) are denoted with $c^{e}_{n,t,1}$, $c^{e}_{n,t,2}$, $c^{e}_{n,t,3}$, $c^{e}_{n,t,4}$ and $cp_{n,t}$ respectively. Round trip efficiency (PSHP technology efficiency coefficient) is denoted by $\eta$. The probability of being engaged in $h_{n,t,1}$, $h_{n,t,2}$ and $h_{n,t,3}$ is expressed by $v_1$, $v_2$ and $v_3$, respectively.

In (1), the first, second and third expressions refer to the income earned from the capacity in the regulation-up, regulation-down and spinning reserve, respectively. The fourth and sixth expressions from (1) relate to extra income when the storage produces energy in regulation-up and spinning reserve services, while the fifth expression refers to refunding for unproduced energy in regulation-down service. The seventh and eighth expressions from (1) relate to energy selling and pumping.

## III. Numerical Examples

In numerical examples, the operation of the PSHP open-loop system with 300 MW power in producing mode, 250 MW power in pump mode and the round-trip efficiency coefficient of 75%, was optimized. The minimum operating power in producing mode was 60 MW. The upper and lower reservoirs' volumes were $6\cdot 10^6$ m$^3$ and $3\cdot 10^6$ m$^3$, the inflows in these reservoirs were $0.07\cdot 10^6$ m$^3$/h and $0.02\cdot 10^6$ m$^3$/h, while the net elevation of the upper reservoir was 300 m. The capacity limits for ancillary services such as regulation-up, regulation-down and spinning reserve were 39 MW, 39 MW and 30 MW, respectively.

The PSHP construction costs were calculated as the sum of the costs proportional to the nominal plant power and the costs proportional to the capacity of both reservoirs. In our calculations, unit prices of power and storage capacity (which vary significantly according to local conditions) were taken from [18] (including inflation until 2019), while unit operation and maintenance (O&M) cost was taken from [19]. All unit prices for 2021 were additionally increased by 5% due to the increase of all the above-mentioned prices. These prices are shown in Table I.

TABLE I
THE INVESTMENT, OPERATION AND MAINTENANCE UNIT PRICES

| Item | 2019/2020 | 2021 |
|---|---|---|
| Cost per unit of power rating (€/MW) | 1,828,000 | 1,919,400 |
| Cost per unit of storage capacity (€/MWh) | 178,000 | 186,900 |
| Unit O&M cost (€/MW/year) | 2,700 | 2,835 |

The comparison of the incomes that the above-mentioned reversible hydropower plant could generate from energy arbitration and ancillary services in one year was made considering the prices achieved in the Nord Pool market in 2019, 2020 and 2021. As the COVID-19 pandemic began at the end of 2019, it is reasonable to take prices in 2019 as baseline values, and 2020 and 2021 as the period of the pandemic impact.

The fluctuation of day-ahead Nord Pool hourly system prices of electricity (market clearing reference prices for the Nordic region) for 2019, 2020 and 2021 were graphically presented in Fig. 1. Statistical analysis of day-ahead and regulating prices (average of minimum and maximum daily prices as well as average and median of hourly prices in each of the observed years), given in Table II, indicates an incredible reduction in electricity prices on the day-ahead market in the first wave of the pandemic (approximately 2020) of about 4 times, and then an even greater increase in electricity prices after the COVID-19 crisis was evidently mitigated (approximately 2021) by 5 to 6 times. Prices on the regulating market in the same period were even more volatile (a drastic drop in 2020, and then an increase of 8 to 10 times in 2021). Furthermore, the standard deviation of hourly electricity prices was higher in 2020 than in 2019, although electricity prices fell extremely, indicating a significantly higher fluctuation (dispersion) of electricity prices in 2020. These characteristics are clearly indicated by the coefficients of variation (or relative standard deviations) defined as the ratio of the standard deviation to the average (expressed as a percentage). The coefficients of variation of electricity prices as well as the coefficients of variation of services prices increased significantly in 2020, and then decreased slightly in 2021, which indicates a trend of decreasing volatility in both markets.

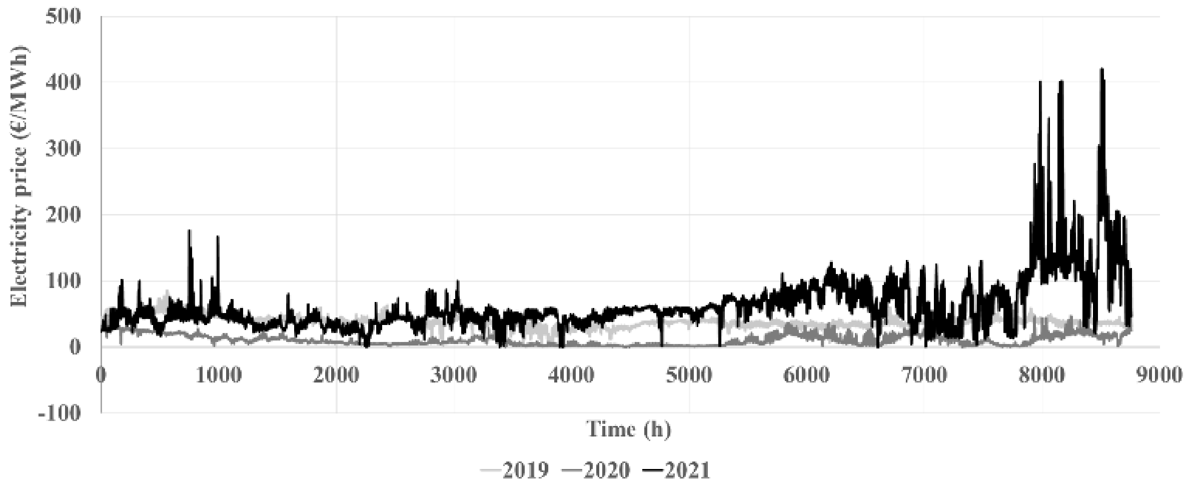


Fig. 1 Day-ahead Nord Pool hourly prices in 2019, 2020 and 2021

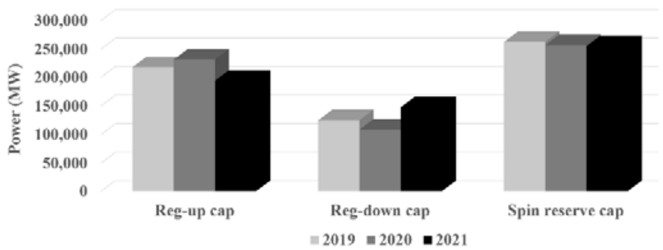


Fig. 2 Annual sums of the offered ancillary services capacities

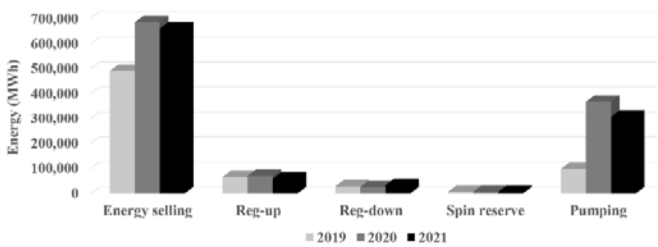


Fig. 3 Annual energy quantities for all services

The results (offered capacities, energies, operation hours and income for all services) obtained by optimizing the operation of the PSHP in the observed years are given in Figs. 2-7.

Energy storage facility capable for providing ancillary services can generate more income from providing services than from energy arbitrage. However, ancillary services requirements, defined by the system operator, are limited. Fig.

2 provides an insight into the annual sums of PSHP capacity offered for ancillary services taking into account the set hourly capacity limits (39 MW, 39 MW and 30 MW for regulation up, regulation down and spinning reserve, respectively) in all numerical examples.

TABLE II
DESCRIPTIVE STATISTICS OF THE NORD POOL MARKET PRICES FOR 2019, 2020 AND 2021

| | | Day-ahead | Reg-up | Reg-down |
|---|---|---|---|---|
| Daily price analysis | Avg. max. 2019 (€) | 43.40 | 48.20 | 42.30 |
| | Avg. max. 2020 (€) | 14.40 | 14.12 | 10.63 |
| | Avg. max. 2021 (€) | 82.00 | 104.49 | 91.30 |
| | Ratio 2019/2020 | 3.01 | 3.41 | 3.98 |
| | Ratio 2021/2020 | 5.69 | 7.40 | 8.59 |
| | Avg. min. 2019 (€) | 33.70 | 35.90 | 30.00 |
| | Avg. min. 2020 (€) | 7.70 | 7.83 | 5.08 |
| | Avg. min. 2021 (€) | 43.00 | 60.55 | 51.39 |
| | Ratio 2019/2020 | 4.38 | 4.58 | 5.91 |
| | Ratio 2021/2020 | 5.58 | 7.73 | 10.12 |
| Hourly price analysis | Median 2019 (€) | 38.70 | 40.00 | 36.50 |
| | Median 2020 (€) | 8.50 | 7.61 | 5.50 |
| | Median 2021 (€) | 52.00 | 60.50 | 54.68 |
| | Ratio 2019/2020 | 4.55 | 5.26 | 6.64 |
| | Ratio 2021/2020 | 6.12 | 7.95 | 9.94 |
| | Average 2019 (€) | 39.00 | 40.70 | 36.60 |
| | Average 2020 (€) | 11.00 | 10.13 | 7.97 |
| | Average 2021 (€) | 62.30 | 78.01 | 68.83 |
| | Ratio 2019/2020 | 3.55 | 4.02 | 4.59 |
| | Ratio 2021/2020 | 5.66 | 7.70 | 8.64 |
| | Std. dev. 2019 (€) | 8.10 | 11.20 | 9.00 |
| | Std. dev. 2020 (€) | 8.30 | 9.20 | 7.97 |
| | Std. dev. 2021 (€) | 42.60 | 50.61 | 43.32 |
| | Coefficient of variation 2019 (%) | 21.00 | 27.50 | 24.74 |
| | Coefficient of variation 2020 (%) | 75.60 | 90.87 | 100.00 |
| | Coefficient of variation 2021 (%) | 68.40 | 64.88 | 62.94 |

Optimal annual amount of energy generated for sale on the day-ahead market, the amount of energy consumed for pumping mode as well as the amount of energy delivered during the provision of regulation and reserve services in 2019, 2020 and 2021 are shown in Fig. 3. The difference between the sum of energies in producing mode (selling, reg-up, spinning reserve) and the sum of energies in reverse mode (pumping and reg-down) in each of the observed years is the energy generated from the natural inflow into the upper reservoir plus losses.

The sum of hours in 2019, 2020 and 2021 of all services involved in income generation were given in Fig. 4.

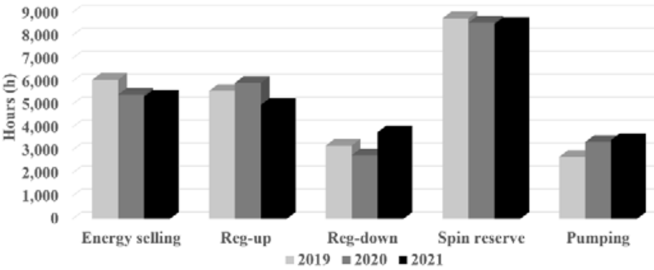


Fig. 4 Annual sums of service provision hours

The absolute values of annual incomes from all services are given in Fig. 5, while the share of individual services in the total income in each of the observed years is shown in Fig. 6. In these figures, the costs for pumping energy and unproduced energy in the regulation-down service are presented as income losses.

From Figs. 2-4, it can be seen that the PSHP operation mode is similar in all of the observed years. The main reason is that both electricity and service prices fluctuate together. In addition, the provision of individual ancillary service involves the simultaneous capacity offering and energy engagement. However, incomes from all services are evidently the highest in 2021 due to significantly higher electricity and services prices. The differences in total incomes in the three observed years can be clearly seen in Fig. 7.

The calculation of the payback period, shown in Table III, took into account the unit prices of investment, operation and maintenance (Table I) and the total annual income (Fig. 7) that PSHP with the above characteristics could generate through energy arbitration and ancillary services in the three observed years, with regard to achieved market prices. The rapid reduction of the payback period, although calculated for the assumed PSHP, clearly indicates the importance of energy storage in crisis and in energy market disruption.

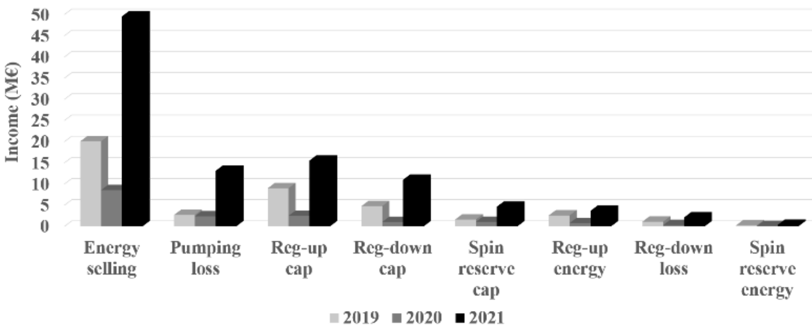


Fig. 5 Incomes from all services

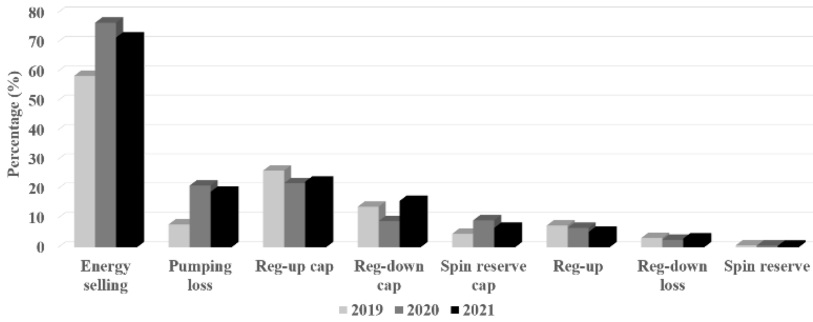


Fig. 6 Services share in the total income

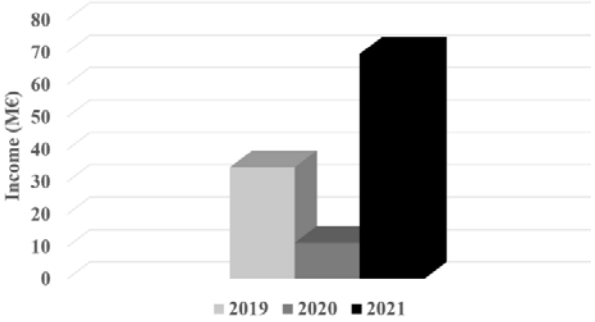


Fig. 7 Income for 2019, 2020 and 2021

TABLE III
THE PAYBACK PERIOD CALCULATION

| | 2019 | 2020 | 2021 |
|---|---|---|---|
| Power rating cost (€) | 548,400,000 | 548,400,000 | 575,820,000 |
| Storage capacity cost (€) | 1,305,968,022 | 1,305,968,022 | 1,371,266,423 |
| Total investment cost (€) | 1,854,368,022 | 1,854,368,022 | 1,947,086,423 |
| Annual storage income (€/year) | 34,358,737 | 11,159,861 | 69,376,232 |
| O&M cost (€/year) | 810,000 | 810,000 | 850,500 |
| Net storage income (€/year) | 33,548,737 | 10,349,861 | 68,525,732 |
| The payback period (year) | ≈55.3 | ≈179 | ≈28.4 |

## IV. CONCLUSION

In this paper, the impact of the electricity market prices on energy storage operation during the COVID-19 pandemic was investigated. Using the Nord Pool prices for 2019, 2020 and 2021, the PSHP optimal operation mode under market conditions was obtained.

- In the first wave of the pandemic, electricity market prices fell considerably. After the COVID-19 pandemic mitigation, energy demands have risen significantly, electricity prices have risen even higher (average price 2021/2020 on the day-ahead Nord Pool market 5.66 times), while ancillary services prices have risen dramatically (7.70 and 8.64 times for average regulation-up and regulation-down prices in the same period). Electricity market prices in 2021 were notably higher than in 2019 (Table II).
- Energy prices and ancillary services prices fluctuations increased significantly during the COVID-19 pandemic (Table II).
- The impact of power market prices during the COVID-19 crisis (as well as other global disastrous events) on the PSHP operation mode is not significant because electricity prices and service prices fluctuate together (Figs. 2-7). The impact of power market prices on annual income as well as on the payback period is enormous (Table III).
- Although 2020 and 2021 prices are not as common as usual and the pandemic is not the only cause of prices fluctuation, it can be seen that in disruption times of power prices, energy storages show their cost-effectiveness and importance.

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