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Increasing the efficiency of pumped storage power plants.

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Abstract. The use of different types of renewable energy sources has been growing very rapidly recently. This is especially true for the use of wind and solar energy to produce heat and electricity. Many advanced countries have already achieved a share of renewable energy sources in the total energy production balance of about 40-50 per cent. This is quite high, although the goal of reducing the level of CO2 in the earth's atmosphere has not yet been achieved. The unstable over time capacity of generation using renewable energy sources leads to additional difficulties in ensuring the reliability of power supply and the quality of generated electricity, which eventually leads to the need for widespread use of energy storage technologies. The most widespread is the system of hydro-pump energy storage. It is practically the only technology to date that allows storing large amounts of energy for a long period of time. The purpose of this study is to analyse in depth the operating experience of hydro-pump energy storage, quantify the efficiency of their operation, and develop the most promising directions to improve their flexibility and efficiency. A detailed efficiency analysis is performed on the example of the hydro pumped storage power plant "Gorona del Viento" (El Hierro Island, Canary Archipelago, Spain). Possible methods of load balancing in the electric network by means of a hydro pumping power plant are considered. Using computational models, the main operating modes of the power plant are analysed, and the possibility of implementing different strategies of load balancing in the electric grid is demonstrated.

Key words. Hydro pumped energy storage, efficiency, power plant flexibility, renewable energy.

1. Introduction

In recent years there has been a very rapid growth in the use of renewable energy sources worldwide. This is particularly true for wind and solar power, which have intermittent generation capacity depending on weather conditions. IRENA's latest World Energy Transitions Outlook report calls for an annual increase in renewable energy capacity of 1000 GW by 2030 to keep the 1.5°C climate target within reach [1]. However, the more solar and wind renewable energy projects are realized, the more storage system capacity will be required. To date, the only technology that can store large amounts of energy and store it for long periods of time is the hydro pumped storage system.

Initially, it was planned that after the introduction of renewable energy sources, load balancing in the electricity grid would be performed by thermal power plants. However, as the share of renewable energy sources in the total balance of electricity generation increased, it became impossible to use old technologies due to the technical capabilities of large thermal power plants. This is why the issue of increasing the flexibility of hybrid power plants with a high share of renewable energy sources has become acute. The best solution to this problem is hydro pumped storage power plants. Moreover, to increase the flexibility of the energy system, modernization projects of existing hydroelectric power plants are being implemented [2]

One of the most typical hybrid power plants is the project "Gorona del Viento", which was released back in 2015 on the island of El Hierro. Figure 1 shows the technological scheme of this power plant with all the main parameters of the equipment [3]. Similar projects have been released on the island of Madeira (Portugal), Ikaria (Greece) and so on.

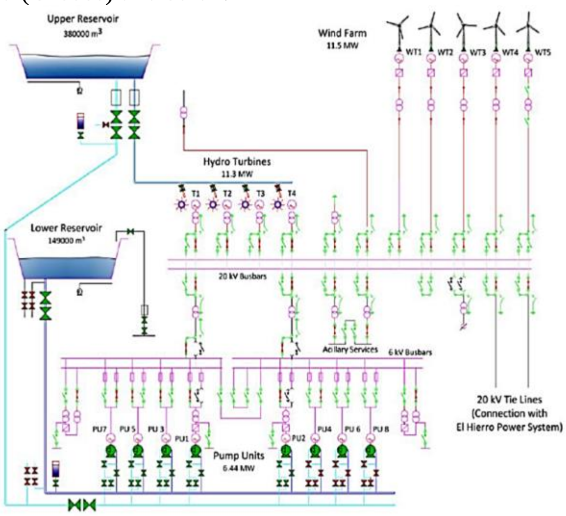

Fig. 1. Process flow scheme of the hybrid power plant "Gorona del Viento" with indication of all main process parameters [3].

As shown in Fig.1, the "Gorona del Viento" project includes five single-type wind turbines with a total capacity of 11.5 MW, a pumping group with a total capacity of 6.44 MW, and a group of single-type Pelton hydraulic turbines with a total capacity of 11.3 MW. At the same time, the pumping group consists of two types of pumps: 4 pumps with a capacity of 0.5 MW each and 2 pumps with a capacity of 1.5 MW and power regulation. The upper reservoir has a capacity of 380 thousand cubic metres of water and the lower reservoir has a capacity of 149 thousand cubic metres of water. An old diesel power plant with a total capacity of 11 MW is used as backup power sources. The water level difference between the upper and lower reservoirs is 665 metros.

The Gorona del Viento project has been in operation since 2015, and naturally a fair amount of research work has been devoted to analysing this project. The first published scientific articles and conference papers published before 2018 contained only a description of the power plant's composition and initial conclusions about the first years of operation [3-6]. These papers did not contain serious analyses, although even at that time researchers noted significant fluctuations in wind power generation capacity and difficulties in ensuring the quality of electricity.

The most detailed analysis of the efficiency of the main elements of the Gorona del Viento hydro pumping power plant is given in the paper [7]. However, the authors' analysis is based only on technical data from equipment manufacturers, but there is no comparison with real data from the experience of operating this equipment for five years. In addition, the authors of this study do not take into account the influence of dynamic modes of equipment operation on their efficiency.

It is also worth noting several works that are devoted to ensuring the frequency of electric current within specified limits [8-10]. This is an extremely important problem in conditions of highly unstable wind power generation capacity. The main difference of these works in contrast to the work [7] is the study of dynamic characteristics of the power plant equipment. However, the main reason for the variation of electric current frequency is the constant imbalance between generation and consumption power, which can be eliminated by increasing the flexibility and efficiency of the hydro pumping power plant.

In work [11], it is proposed to use Pelton hydraulic turbines with some modernization for damping of oscillations during dynamic operation modes to balance the load in the electric network and to maintain the frequency of electric current. This paper is a continuation of the research started by the same authors in work [3]. In the new paper, the authors have already made a more detailed analysis of operating experience, provided some statistical data and investigated the transient behaviour of Pelton turbines. However, the aim of this study is only the improved Pelton turbine wheel speed control algorithm and not the efficiency of the power plant in general and hydro pumping power plant in particular.

The work [12], which, as well as in the previous case, is a continuation of the research started by the authors in the work [7], outlines the algorithm for analysing the efficiency of the "Gorona del Viento" project and provides statistical data on the experience of the project's operation over the last few years. However, some of the data and especially the conclusions of this paper are not sufficiently substantiated and therefore raise certain doubts. For example, the final part of the work [12] states that to achieve 100% utilization of renewable energy sources on the island of El Hierro and increase the efficiency of the Gorona del Viento project, the following is necessary (the text is copied in full of the final part of the work [12]:

- Install at least 10 MW of solar photovoltaic.
- Install batteries with grid-forming inverters.
- Minimize the simultaneous use of turbines and pumps.
- Use another inertial provider such as synchronous condensers, or flywheels.
- If possible, increase wind farm power.

The first, second and last paragraphs of these proposals are not sufficiently motivated in this paper. The third point contradicts the conclusions of paper [11], and the fourth point contradicts the conclusions of paper [12] and point 2 of the same proposals. Also, all these proposals will eventually lead to the need to install a large amount of additional equipment, which will increase the cost of electricity and reduce the utilization rate of the power equipment, which is already very low at the power plant "Gorona del Viento". The only way to justify the proposal of [11] is to consider the project "Gorona del Viento" not as a power plant, but as a test site for the use and research of various renewable energy sources. Only in this case investments in such a project will make sense and be economically feasible.

Most of the above-mentioned authors of the studies recognize the low efficiency of the hydro pumped storage system of the Gorona del Viento project, as well as the lack of flexibility. Suggestions for improving efficiency and flexibility, which are given in the above-mentioned papers, consist mainly in the need to install additional equipment. The only exception is the work [13]. It should also be noted that there is no quantitative assessment of electric energy losses in the above studies.

The closest, in essence, to this study is the work [14], which presents the results of modelling and optimization of hybrid power plants with a hydro pumped storage system. First, it should be noted that the authors of this paper in the literature analysis section conclude that the use of fixed coefficients of power plant equipment efficiency, which were used in the optimization in other studies, including those listed above, are incorrect. However, the authors of [14] in their study use variable coefficients of equipment efficiency, but these coefficients are not obtained by analysing the experience of equipment operation but are taken from the technical documentation of the equipment. Of course, this increases the degree of accuracy of research, but several losses that occur in real conditions are not considered. Dynamic processes are not considered. Also, despite detailed analyses of several hybrid power plants, the authors of this paper come to rather contradictory conclusions at the end of their study. The goal of this study is to optimize the economic performance of the power plant, but at the same time the authors of this study recognize that each power plant has quite significant differences in terms of construction and operating costs.

This results in different economic criteria. Thus, the difference between this study and the results of [14] lies primarily in the final objective of the optimization and the chosen criteria for performance evaluation. Although the methods of analysis partially coincide.

2. Analysing the operational experience of the Gorona del Viento hydro pumping power plant.

The Gorona del Viento project has been in operation for almost 10 years. Pilot operation of the project started back in mid-2014. For almost three years, the equipment of this power plant continued to be fine-tuned. Since 2018, the operation of the hybrid power plant "Gorona del Viento" has become more stable. During the previous years, sufficient experience in the operation of the equipment was gained and the errors of the initial phase were considered.

Since 2018, sufficiently high utilization rates of wind energy for electricity generation have been achieved. Figure 2 shows the results of wind energy utilization for electricity generation. The average annual share of wind energy utilization in the total balance of electricity generation after 2018 was more than 50%, and in some months, as can be seen from Figure 2, it was almost 100%.

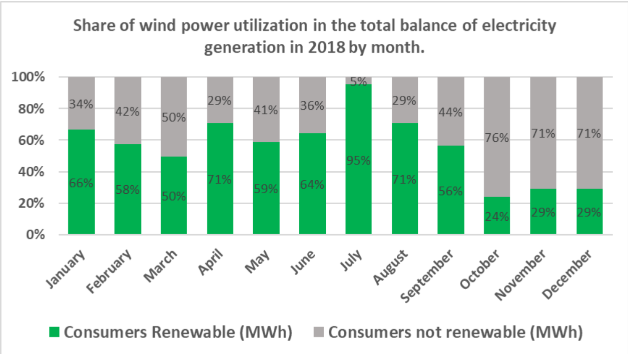

Figure 2. Share of wind power utilization in the total balance of electricity generation in 2018 by month.

This high result was possible because of the hard work of the company's employees and several research institutes in several countries.

Every year Gorona del Viento El Hierro, S.A. publishes a report on the operation of the power plant, one of which is shown in Figure 3 [15-17]. In the bottom right corner of Figure 3, the green arrow marks the results of electricity production for each month of 2019, and the red arrow shows the final figures of the energy balance of the entire equipment complex of the power plant. By collecting data for all years of operation, we can estimate the average efficiency of the hydro pumping power plant. The results of this analysis are presented in Figure 4.

As can be seen in Figure 4, for the first three years of operation of the hybrid power plant, load balancing in the power grid was mainly performed by diesel generators. In the period 2015-2017, diesel generators were operated almost continuously to ensure the reliability of electricity supply to consumers. However, this led to an artificial increase in excess electricity and consequently the efficiency of the energy storage system was extremely low. Electricity losses in these years totalled more than 25 GWh per year, which is almost 70 per cent of all electricity generated from wind power.

From 2018 onwards, diesel generators were switched off and load balancing was done to a greater extent with a hydro storage system. Diesel generators were used only during periods of wind power shortages and to prevent emergencies. This increased the efficiency of the energy storage system to 42-45% and reduced the average annual electricity losses to 10 GWh. On the one hand, this result is confirmed by the findings of [12], where the author comes to similar conclusions. On the other hand, this result completely refutes the conclusions of the authors of [11] and [18], who use in their calculations the average annual efficiency of about 65-72%.

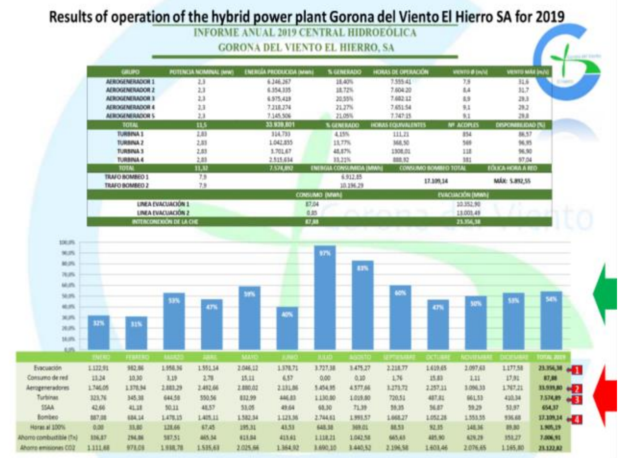

Fig. 3. Annual report of Gorona del Viento El Hierro, S.A. for 2019 [15].

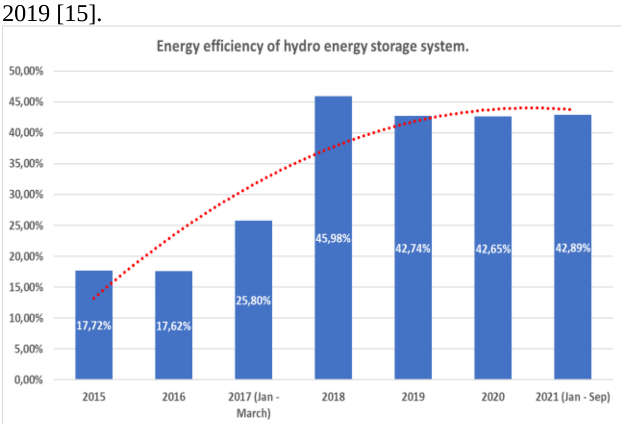

Fig. 4. Average annual efficiency of the hydro storage system from 2015 to mid-2021.

The use of the energy balance algorithm, as well as data from the annual reports, allowed us to make a preliminary analysis of the efficiency of the Gorona del Viento project, the results of which are shown in Figure 5. Also, Figure 5 shows some data obtained by other authors. As a result of the energy balance algorithm, it was possible to quantify the electrical energy losses of the Gorona del Viento hybrid power plant and to identify the main causes of these losses.

As shown in Figure 5, during the last 5 years it has been possible to almost halve the use of diesel fuel to produce electrical energy on the island of El Hierro, however, the specific fuel consumption to produce 1 MWh using diesel engines has slightly increased, indicating a decrease in their efficiency. Figure 5 also shows that the main losses are associated with the hydro energy storage system and account for almost 30% of the total electricity generated from wind power.

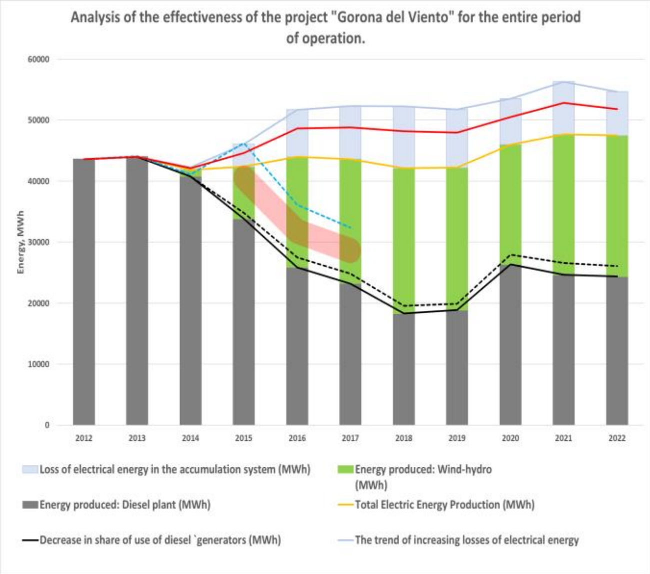

Fig. 5. Results of analysing the efficiency of the hybrid power plant "Gorona del Viento" since its inception using an energy balance algorithm.

However, the energy balance algorithm allows estimating the efficiency of individual elements of the power plant and estimating the amount of electricity losses but does not allow identifying the causes of these losses. For a more detailed analysis of the efficiency of all elements of the hybrid power plant "Gorona del Viento", a digital twin of the power plant was developed in MatLab Simulink. The schematic diagram of the digital twin is presented in Figure 6.

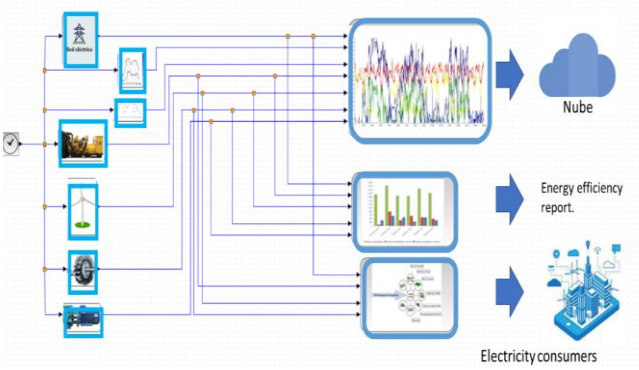

Fig. 6. Schematic diagram of the digital twin of the power plant "Gorona del Viento" created in MatLab Simulink environment.

After detailed analysis, the results are displayed on a dashboard for visualization, which is shown in Figure 7. The first screen of the dashboard shows summary data of the power plant operation and to some extent repeats the previous analysis using the energy balance algorithm. However, this screen allows for detailed analysis of data for a selected year and month, which significantly expands the analysis capabilities. The first screen of the dashboard also displays regression analyses of wind-powered generation capacity as a function of wind speed, which will then be used to predict the capacity of the hydro pumped storage system. These two screens allow the most problematic periods of power plant operation to be visually identified in terms of efficiency. The system then allows the selected period to be detailed in 10-minute increments and the operation modes of the Pelton pump groups and turbines to be analysed. The results of this analysis are shown in Figure 8.

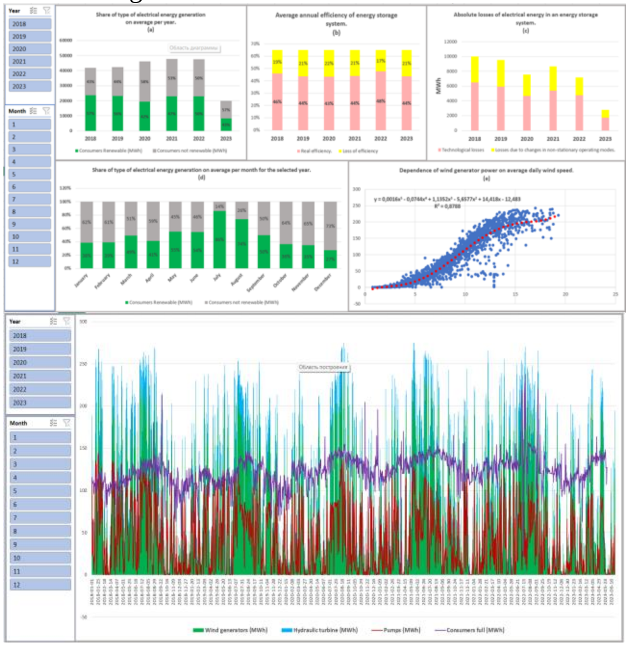

Fig. 7. Dashboard of the hybrid power plant on the island of El Hierro.

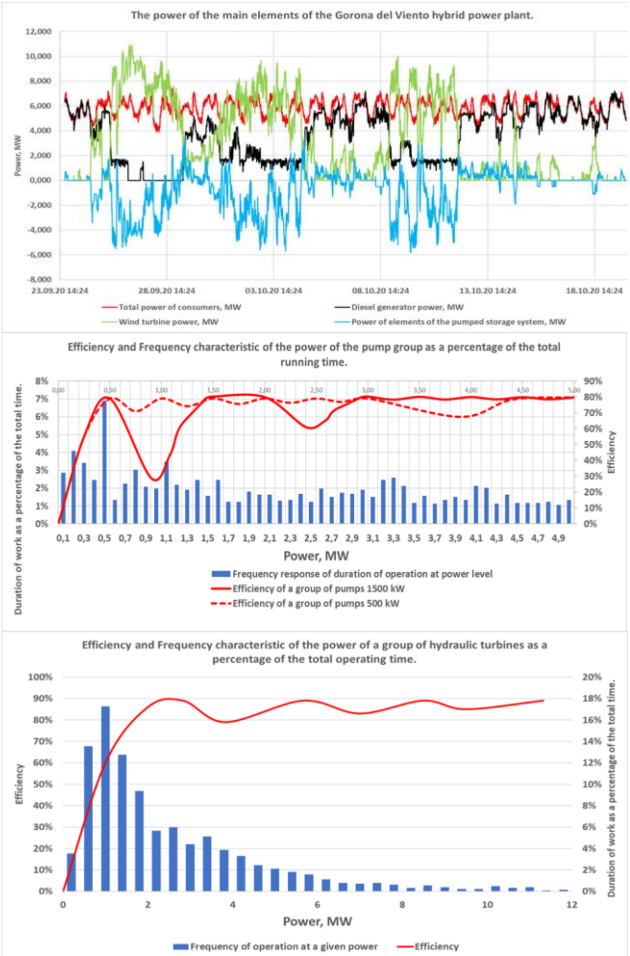

Fig. 8. Detailed performance analysis of the Pelton pump groups and turbines of a hydro energy storage system.

The last two graphs in Figure 8 clearly show that the reason for the low efficiency of the Pelton pump groups and turbines is their long enough operation at low efficiency modes. This explains the low average efficiency compared to the maximum (theoretically achievable) efficiency. The conducted detailed analysis allows us to conclude that it is possible to increase the efficiency of hydro pumping power plant by applying an effective control system, which will avoid the use of inefficient modes of operation during the operation of the equipment. However, it is difficult to build an effective control system without accurate forecasts of renewable energy generation capacity and electricity demand.

3. Short-term forecasting of the imbalance between wind generation capacity and electricity demand.

The defining parameter that allows optimizing the operation of the entire power system and the hydro pumped storage system is the imbalance between generation capacity and demand for electricity. It is the maintenance of the imbalance value within the specified limits that allows to ensure the reliability of power supply to consumers and the quality of generated electric energy. It is the imbalance between generation capacity and demand for electrical energy that determines the operation of Pelton pump groups and turbines.

Many different algorithms for forecasting generation capacity using wind and solar power as well as electricity demand are proposed in the technical literature [19,20]. Based on the resulting forecasts, it is of course possible to calculate the magnitude of the imbalance between generation capacity and electricity demand. However, each forecast of generation capacity and electricity demand has its own error, and because of calculating the imbalance value in this way, these errors will be summed up. As a result, forecasting the imbalance between generation capacity and electricity demand will be inefficient.

A more accurate imbalance forecast can be obtained by training an autoregressive neural network. In this case, we need to use the imbalance time series itself, the time series of electricity demand, and the time series of generation capacity with wind and solar power as input data. Only in this way can we obtain a sufficiently accurate forecast. Figure 9 shows the results of forecasting the imbalance between generation and electricity demand using the LSTM Network.

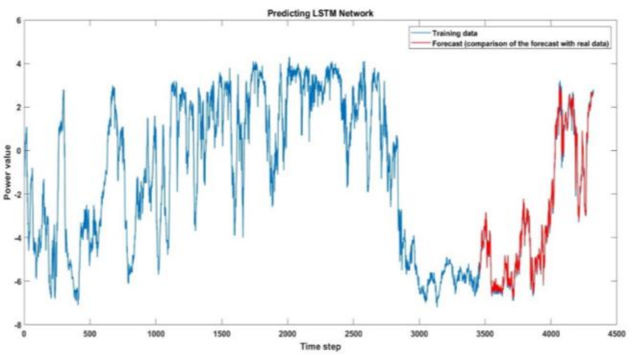

Fig. 9. Results of forecasting the imbalance between generation and electricity demand using LSTM Network.

4. Optimization of hydro pumping power plant operation.

From the very beginning of the project, it was planned that the hydropower plant would only perform the energy storage function and that load balancing in the grid would be carried out by diesel generators, as has been the case in the past. However, as the first three years of operation have shown, this strategy has resulted in very high losses, as can be clearly seen in Figure 5. Diesel generators, due to their technical characteristics, simply cannot compensate for the generation imbalance that is created by wind turbines.

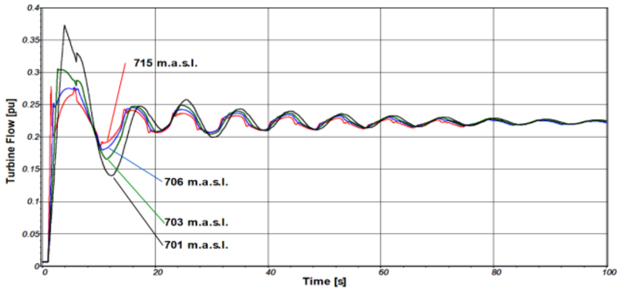

Fig. 10. Turbine water flow after a wind generator trip for different upper reservoir levels (100 s) after a 2.3 MW wind generator trip [13].

Starting in 2018, the hydro pumped storage power plant began to fulfil two functions at once: accumulation of excess load and load balancing in the electric grid. This is a logical solution and has improved the efficiency of the entire power plant. Pelton turbines have a high efficiency (85-90% for outputs above 400 kW) and manoeuvrability. The latter has been analysed in detail in [13]. Figure 10 shows one of the graphs of this work, from which the Pelton turbine can quickly gain power (less than a minute) at a complete shutdown of generation using wind power.

However, things are a bit more complicated with the pumps. The pumps are also quite manoeuvrable, but as mentioned at the very beginning, the Gorona del Viento power plant has six 500 kW fixed capacity pumps and two 1500 kW variable capacity pumps. This means that smooth load balancing in the grid is only possible when the pumps and Pelton turbines work together. Such mode of operation, as a rule, leads to large losses of electrical energy. The authors of [12] in their study believe that it is necessary to minimize such mode of operation. This thesis can be confirmed or refuted by the following analysis.

The power of the Pelton hydraulic turbine and the pump power can be determined by the formulas:

$$P_t = 9{,}81 Q_{wt} H_t \eta_t \qquad \text{Turbine equation} \qquad (1)$$

$$P_p = \left(9{,}81 Q_{wp} H_p\right)/\eta_p \qquad \text{Pump equation} \qquad (2)$$

Where:

P_t, P_p- hydraulic turbine power and pump power respectively.

Q_{wt}, Q_{wp}- water flow rate through the turbine and pump capacity respectively.

H_t, H_p - water head in front of the turbine and pump head respectively.

η_t, η_p - efficiency factor of turbine and pump respectively.

Electrical energy losses can be defined as the ratio of turbine power to pump power ((P_t/P_p).).

After reducing the same values, we obtain the following expression for determining the losses:

$$\eta = \frac{H_t}{H_p}\eta_t\eta_p \qquad (1)$$

At stationary operation (according to the technical documentation and data of [13]) the head of the pumps is 690 metros of water column, and the water head in front of the turbine due to hydraulic resistance of the pipelines is 651-658 metros of water column depending on the water level in the upper reservoir. Consequently, the hydraulic losses in the pipelines result in an additional loss of about 5 per cent. Plus, losses in the pump and turbine - about 25%, which will be in any case in the hydro storage system.

Let us take an example from the Gorona del Viento hybrid power plant. Figure 11 shows the pump and turbine schedules for three days. The lower part of the graph (in the negative part) shows the output of the Pelton turbine, which has good manoeuvrability and the ability to smoothly adjust the output over the whole range. Therefore, the graph power of Pelton turbine is fully matched with the required power to compensate the shortage of electrical energy in the grid. And the upper part of the graph (the positive part) shows the graph of the excess power and the power of the pumps with fixed power, assuming that only the pumps are operating. Because the pumps have a fixed power, and the excess power varies over a wide range, there are additional losses in the order of 100 to 400 kW. If we summarize the data for this period, the excess capacity of the wind turbines was 64.5 MWh, while the pumps consumed only 57.6 MWh. Consequently, if only the pumps were operating without the Pelton turbines, the additional losses amounted to 6.9 MWh, which is just over 10%.

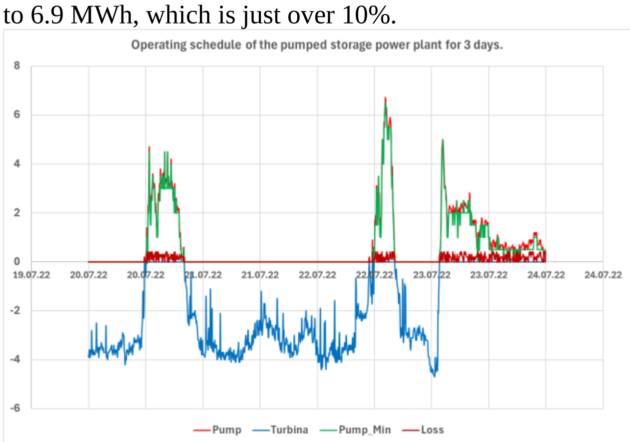

Fig. 11. The schedule of the hydro pumping power plant for three days.

Many researchers have suggested replacing fixed power pumps with speed and power consumption-controlled pumps, arguing that this would provide a smooth adjustment of the total power consumption. However, calculations show that this will lead to even greater losses of electrical energy. The problem is that variable speed pumps are only highly efficient at maximum power. When power is reduced, their efficiency drops dramatically.

Figure 12 analyses the efficiency of the variable speed pumps over three days. The histogram shows the frequency of pump operation at a certain power level in 100 kW increments. The colour of the histogram bars changes depending on the efficiency of the pump at that mode. A red-coloured bar corresponds to the pump operating at less than 50% efficiency in that mode, a light green coloured bar corresponds to 60-70% efficiency, and only a green coloured bar corresponds to a maximum efficiency of over 70%. As can be seen from Figure 12, variable speed pumps will operate at medium efficiency most of the time, resulting in a loss of about 20 %.

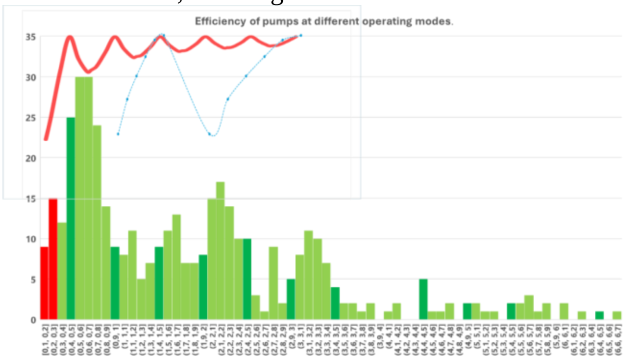

Fig. 12. Histogram of pump frequency at certain power levels (■ - Pump efficiency less than 50%, ■ - Pump efficiency 60-70%, ■ - Pump efficiency over 70%).

The upper part of Figure 12 shows the efficiency graphs for 500 kW (red line) and 1500 kW (blue dashed line) variable speed pumps. It should be noted that the use of 1500 kW variable speed pumps results in even higher energy losses compared to the 500 kW pumps.

The above analysis clearly shows that the energy losses when pumps and Pelton turbines operate together are comparable to, and in some cases less than, the losses when pumps alone operate, both fixed power and variable speed.

If the pumps were to use all the excess electrical energy, there would be some shortage of electrical energy to supply the fixed horsepower pumps. Figure 13 shows graphs of the surplus and shortage of electrical energy to drive the pumps. The surplus corresponds to the case shown in Figure 13 and the shortage corresponds to the case where the pumps have fully utilized all the surplus energy in the grid.

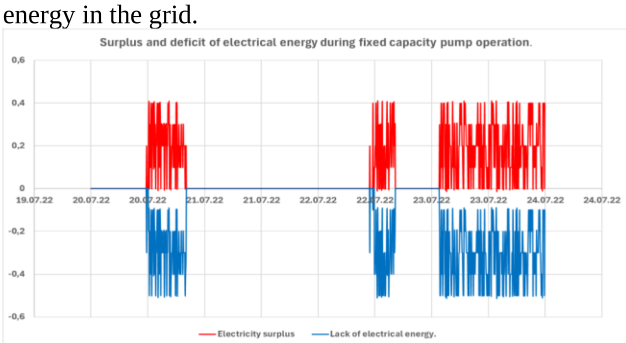

Fig. 13. Surplus and shortage of electrical energy to provide fixed capacity pumps.

A hydraulic turbine can be used to compensate for the lack of electrical energy. This option has several advantages. Firstly, the pumps will run continuously at maximum efficiency. Secondly, the inertia of the turbine will significantly reduce the frequent switching on and off the pumps, thus the operation of the pumps will be stable. Thirdly, as will be shown later, this option will significantly increase the flexibility of the whole hybrid power plant.

To confirm this thesis, it is powerful to cite the simulation results of pump operation under different modes, which were given earlier using real data Figure

11. Table 1 shows the simulation results of different pump operation options.

Table 1. Simulation results of pump operation at different modes.

Parameter	Option 1 Operation of fixed capacity pumps.	Option 2 Variable speed pump operation	Option 3 Combined operation of Pelton pumps and turbines
Quantity of surplus electric energy, MWh	64,44	64,44	64,44
Quantity of electric energy used to drive the pumps, MWh	57,63	64,44	75,13
Electricity losses, MWh	6,82	0	0
Electricity shortage for pump drive, MWh	0	0	-10,68
Estimated amount of water pumped into the upper reservoir, m3	24202	25600	23107
Change in efficiency compared to the first option.	0	+5,8%	-4,5%

It should be noted that all calculations were made without considering the losses during start-up and stopping of the pumps, which will naturally lead to a decrease in the efficiency of the pumping group. This applies to a greater extent to the first variant. In the case of the second and third variants, smooth operation of the pump group can be ensured. The results in Table 1 are therefore rather approximate and should be considered as qualitative rather than quantitative indicators.

The efficiency and flexibility of the hydro pumped storage power plant can be significantly increased by using a pneumatic-hydraulic accumulator as part of the hydro pumped storage power plant, the scheme of which is shown in Figure 14.

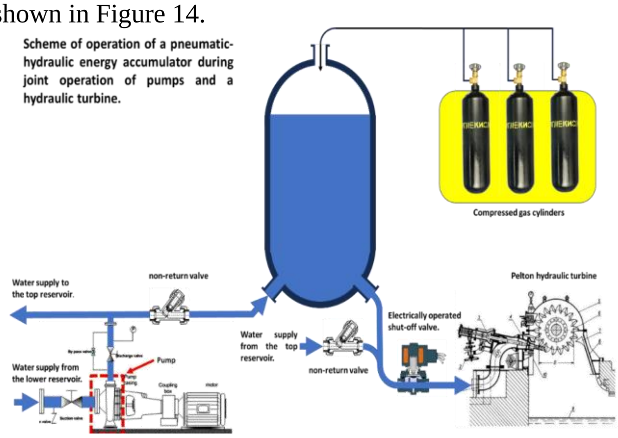

Fig. 14. Scheme of operation of a pneumo-hydraulic energy accumulator during joint operation of pumps and a hydraulic turbine.

The principle of operation of such a circuit is as follows. The pump runs continuously at maximum head. Part of the water after the pump is fed into the pneumo-hydraulic accumulator until the gas pressure in the upper part reaches the value of the maximum pump head. If the excess capacity of the wind turbines is insufficient, an electrically operated shut-off valve is opened and the water from the pneumo-hydro accumulator is fed to the Pelton turbine, which generates the missing electricity. Gas cylinders ensure a constant water head as the water level changes. In case of water shortage in the pneumo-hydro accumulator, water is supplied from the upper tank.

Compared to the variant proposed in [13], the proposed variant of using Pelton turbine for load balancing has the following advantages:

Firstly, all pumps operate at maximum power with maximum efficiency. The energy losses in the pumps due to operating at reduced power are eliminated.

Secondly, we use some of the surplus energy from renewable energy sources for load balancing in the electricity grid. Otherwise, this excess energy would be sent to the energy storage system and most or all of it would be irretrievably lost.

Thirdly, the water head at the pump outlet at maximum output is 690 metres of water column. Part of this head is used to overcome the hydraulic resistance of the pipework. As a result, the head in front of the Pelton turbine when using water from the upper reservoir is a maximum of 658 metres of water column. Thus, the hydraulic resistance losses of the pipelines are eliminated.

Fourthly, the most dangerous moment for the reliability of power supply and maintaining the frequency of electric current within the specified limits is the period of a sharp drop in the capacity of generation using wind energy. In this case, an operating Pelton turbine can quickly take over the load and equalize the negative imbalance in the grid. The capacity reserve of the Pelton turbine is at least 50% of the average daily load in the grid. In this way, the flexibility of the hybrid power plant will be significantly increased.

4. Conclusion

First, it must be recognized that existing hybrid power plants, similar in configuration to the Gorona del Viento project, have a huge potential to increase the efficiency of renewable energy sources and the flexibility of the isolated power system. At this point in time, the losses of electricity already produced by wind turbines are more than 30 per cent. At the same time, these losses are mainly related to sharp fluctuations in wind power generation capacity and to the technological features of the hydro pumped energy storage technology used. Reduction of these losses of electric energy will allow to significantly increase the share of renewable energy sources in the total balance of electric energy production using only existing equipment. Adding generating equipment in addition to the already available equipment will only lead to an increase in electricity losses and to the need to significantly increase the capacity of the energy storage system.

A detailed analysis of the operating experience of the Gorona del Viento project for the period from 2018 to 2023 allowed us not only to quantify electricity losses, but also to identify the main causes and determine the dependence of these losses on the operating modes of the equipment. The latter further allowed the construction of a sufficiently accurate

For reliable and high-quality power supply to all consumers of electric energy, hybrid power plants should have flexibility of almost 100% of the consumption capacity. This is since the generation capacity using wind energy can drop from its maximum value to zero within a fairly short time. As has been shown in this study, the rate of drop in wind power generation capacity can be more than 0.5 MW per minute. Consequently, additional equipment or energy storage system must be able to compensate for this rate of power drop. This can only be achieved if the standby generator is brought online in advance and synchronized with the grid. In fact, to achieve this, the standby generator must be permanently on "hot standby" or constantly operating at a minimum power level to take the full load quickly enough within a short period of time.

As shown in this study, the best solutions that will simultaneously improve both the efficiency and flexibility of a hybrid power plant are the use of air-hydro accumulators to allow the Pelton turbines and fixed capacity pumps to work together efficiently.

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