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# Unlocking the flexibility potential of the Čierny Váh hydropower plant through innovative modernisation, integrating battery hybridisation to improve the supply of secondary reserve power to the Grid

**Authors:** Quentin BOUCHER (SuperGrid Institute, France), Tomáš ŠIMOVIČ (SEAS, Slovakia), Fabien GRAND PERRET (SuperGrid Institute, France)

## Abstract

The SE Integrator project<sup>1</sup> consists of the modernisation of the Čierny Váh pumped storage hydro power plant (6 x 122.4 MW) owned and operated by Slovenské Elektrárne (SEAS). It is now in the procurement phase to modernise two of the existing turbines with variable speed turbines hybridised with a battery to drastically increase the grid regulation capacity, in particular the provision of aFRR. With this project, Čierny Váh PHSP will play a key role in stabilising the grid in the region. SEAS and SuperGrid Institute investigated and optimised the technical and economic added value of hybridising the two refurbished units with a utility-scale lithium-ion battery.

The article first describes the SE Integrator project and the technical benefits of different sizes of Li-ion battery. It then presents the economic benefits of hybridising the Čierny Váh pumped storage plant and provision of aFRR balancing capacity in baseload mode. Finally, the article concludes with the optimal battery sizing and associated control strategy to be implemented.

## 1. The SE Integrator project

The SE Integrator project, led by Slovenské Elektrárne, currently in its procurement phase, constitutes a significant advancement in the modernisation and hybridisation of energy infrastructure in Slovakia. Centred on the Čierny Váh pumped-storage hydroelectric power station, the largest facility of its kind in the country with a total storage capacity of approximately 3,900 MWh, enabling it to generate electricity for up to five and a half hours at full turbinating power. The project aims to address both ageing equipment and the increasing demand for flexibility in a renewable-oriented electricity system. In service since 1982, Čierny Váh plays a fundamental role in grid stability and operational flexibility. Its refurbishment within the SE Integrator initiative seeks to extend the plant's lifetime by at least 25 years while significantly improving its technical performance. Two of the six ternary units will undergo full-scale modernisation, which will enhance operational flexibility and raise the maximum operational turbine output from the original 110 MW to more than 122 MW. These improvements are expected to ensure safe, efficient, and reliable operation at a time when the need for grid support and renewable integration is progressively increasing.

A defining aspect of the SE Integrator project is its forward-looking approach to energy storage. In parallel with the hydropower upgrades, the project includes the installation of a large lithium-ion battery energy storage system (BESS) at Čierny Váh. This BESS complements the pumped-storage units and enhances the overall flexibility of the site. In particular, the battery system will enable rapid response to balancing requirements, including the provision of Frequency Containment Reserve (FCR) and automatic Frequency Restoration Reserve (aFRR). By doing so, the integration supports system stability and reliability, while facilitating the management of intermittent renewable generation, notably from solar and wind resources. The study presented in this paper aims at dimensioning this battery and outline the corresponding control strategy. It was conducted jointly by SuperGrid Institute and Slovenské Elektrárne.

This combined approach - refurbishing hydropower units while integrating advanced battery storage - establishes SE Integrator as a leading example of hybrid grid management. It enables Čierny Váh to operate across a broader operational range, allowing greater participation in balancing markets and promoting the effective integration of renewable energy at both national and European levels. The combined system can thus offer rapid, flexible, and low-carbon services to the Slovak electricity grid, directly contributing to both national and European climate objectives. As a Project of Common Interest recognised by the European Commission, SE Integrator aligns with

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<sup>1</sup> More information can be found at <https://integrator-se.sk/>

major energy and climate initiatives such as the European Green Deal and the “Fit for 55” package, reflecting its contribution to system resilience, renewable integration, and emissions reduction.

The fact that the hybrid system can manage set points across a very wide operating range is not only useful for balancing provision. Part load constraints and minimum up and down times create friction in fast paced continuous intraday trading. It is expected that the combined system will allow trading the wide operating range created by the combination of the battery and the modernised units. The system will directly address the intraday trading frictions by enabling rapid modulation of output and decoupling physical generation of the units from market dispatch using the degree of freedom provided by the battery. Therefore other than enhancement of balancing capability, the system is expected to enhance also intraday trading profitability. This article focuses however only on the economic benefits of enhanced balancing provision.

The implementation of the SE Integrator project is planned over a 52-month period, with Works scheduled to start in November 2026 and completion for funding purposes scheduled for April 2031. At the time of writing this paper, the project is in the procurement phase. By combining established infrastructure with new technological solutions, the project maximises the use of existing assets while minimising environmental and social impacts. Overall, SE Integrator reflects Slovenské Elektrárne’s commitment to delivering clean, intelligent, and flexible electricity services, and sets a benchmark for future modernisation initiatives both in Slovakia and across the wider European region.

These benefits extend well beyond Slovakia’s borders. The Slovak electricity system is highly interconnected with neighbouring countries, and relevant markets are increasingly international in scope. Day-ahead and intraday markets already operate on a cross-border basis to ensure optimal dispatch, while new balancing platforms such as PICASSO (aFRR) and MARI/ALPACA (mFRR) are enabling joint European procurement of flexibility. The additional aFRR balancing services delivered by the project will be very useful for the wider region in case the coal phase out of the Czech Republic and Poland creates a shortage of aFRR capacity from spinning generation. In this context, the resilience and security provided by SE Integrator contributes directly to regional and EU-wide system stability, as the value of flexibility and balancing services does not stop at national borders.

## 2. Methodology

This study conducted jointly by SuperGrid Institute and Slovenské Elektrárne aims at dimensioning the battery to be installed at the Čierny Váh pumped-storage hydroelectric power station and outline the control strategy enabling SEAS to get the most profit out of it. It focused solely on the battery and the two units to be modernised. The study was made of two parts giving a complete picture of the performances of the different options:

- A multi market placement optimisation to review the economic performance of the different options
- A schedule simulation study to review the operational indicators associated to the different options

Details on the multi market placement optimisation (inputs, main hypothesis, difference {battery} – {base case}, output schedules...)

The revenues of the PHS are estimated based on a dispatch model. It optimises the pumped storage plant’s dispatch (i.e. electricity generation and consumption) across three market segments:

- Day-ahead (‘DA’) market;
- Automated Frequency Restoration Reserve (‘aFRR’) capacity; and
- Other revenue from spinning reserve not used for balancing capacity: Intraday trading and aFRR balancing energy, expressed as revenue per MW/h of available aFRR+/- spinning reserve capacity.

The dispatch model is formulated as single-stage co-optimisation of the aforementioned three market segments over a 24-hour dispatch horizon. The optimization model contains standard unit commitment constraints and uses a flat round trip efficiency value. A nonlinear version of the model is also available with realistic efficiency curves but this version was not used to generate results in this paper. Other than this study the dispatch model is also used to estimate possible cashflows based on hourly fundamental curves for 2030 and beyond for the purposes of the business case of the SE Integrator project.

For the transient hydraulic simulations, the modelling framework operates on a fine temporal resolution, typically on the order of one second, to accurately capture the dynamic behaviour of the system. Each hydraulic component

is modelled explicitly, with head and efficiency continuously updated at each time step to account for the nonlinear interactions between turbines, conduits, and control structures. This approach contrasts sharply with long-term optimization studies, where simplifications are introduced to reduce computational burden and emphasize broader operational trends rather than instantaneous system dynamics. In contrast, transient analyses prioritize physical fidelity and system security, particularly with respect to surge phenomena, cavitation risks, and load rejection events. In the present study, the transient simulations conducted by SuperGrid Institute enable the evaluation of detailed operational performance indicators over the full annual simulation period. These include the actual number of start-stop cycles of hydro units (including cycles induced by battery recharging), equivalent battery cycles, and the state of charge of the storage system at each time step.

Three different Li-Ion battery sizing are reviewed in this study:

- 80 MW / 160 MWh
- 100 MW / 200 MWh
- 125 MW / 250 MWh

All of these battery sizing were chosen both because their characteristics fit the electrical system of the plant and because of the prices of the corresponding transformers.

Finally the study explored basic hybridisation of the Čierny Váh hydropower scheme with a battery as well as a more advanced control strategy developed by SuperGrid Institute: the eXtended Operating Range (XOR) technology. This Energy Management System (EMS) controlling the energy storage system together with hydropower units leverages the capabilities of the hydro units and the hydro storage to minimize the sizing of the battery while extending the operating range of the installation and providing much more regulation capabilities. The technology is developed to increase the flexibility of hydraulic turbines. It enables the installation to provide automatic frequency regulation (FCR and aFRR) around 0 MW set point. Most interestingly it enables to provide more frequency regulation than the battery capacity around 0 MW set point, which makes it more profitable than the same battery standalone. It also enables the hydropower plant to provide more frequency regulation than separated battery and hydro units at many other operating points.

### **3. Battery sizing options**

#### **3.1. 80 MW / 160 MWh battery**

The addition of a 80 MW / 160 MWh battery to the Čierny Váh hydropower scheme was first studied together with the two variable speed units upgrades.

In the case of a basic hybridisation with the battery, the 80 MW battery can provide up to 80 MW of upward or downward aFRR depending on its setpoint and the state of charge. Besides each of the two variable speed hydro units can provide up to 100 MW of upward or downward depending on their setpoint while turbinating and a maximum of 33 MW while pumping.

In the case of the advanced control of the hybridisation with the battery (XOR technology), besides the previous performance, the Energy Management System developed by SuperGrid Institute enables to combine the two to provide up to 130 MW of upward aFRR from the 0 MW hydro setpoint.

The multi-market optimisation for 2030 indicates that, in the basic hybridisation case, the battery primarily engages in arbitrage on the spot market, selling approximately 120 GWh of energy while consuming around 140 GWh. In parallel, it provides upward and downward aFRR for over 7,000 operating hours, corresponding to about 390 GW·h (Figure 1 and Figure 2). This results in an additional annual revenue of roughly €20 million for the power plant, leading to an estimated payback time of about three years for the battery investment.

In contrast, the optimisation with the advanced XOR control strategy slightly reduces battery arbitrage (approximately 110 GWh sold and 130 GWh consumed) to provide aFRR in XOR mode during periods when the hydro units are offline (0 MW) for about 680 hours annually as can be seen on Figure 1. This allows the Čierny Váh power plant to contribute an additional 17 GW·h of aFRR to the system (Figure 2), generating an extra €4 million in revenue compared to the basic hybridisation scenario.

The multi-market optimisation also provides the hourly schedule for the power plant, which is then used by the schedule simulation to compute technical indicators over the 2030 year. As outlined above, the solution with advanced hybridisation provides more aFRR to the system; consequently, the technical indicators exhibit more

flexible operating behaviour. In particular, the number of starts and stops of the two hydro units increases from an average of about five per day for the basic hybridisation to about nine per day for the advanced Energy Management System solution, in order to recharge the battery. Both solutions, however, show about two equivalent battery cycles per day on average. Finally, the battery state of charge and aFRR imbalances are more effectively managed by the advanced hybridisation. Besides these deviations occur mainly during periods when the XOR mode is inactive in the case of the advanced Energy Management System solution. This outcome confirms the efficiency of SuperGrid Institute control strategy, explicitly designed to minimize imbalances as well as excessive charging or discharging events.

### **3.2. 100 MW / 200 MWh battery**

The addition of a 100 MW / 200 MWh battery to the Čierny Váh hydropower scheme was also analysed in this study.

In the case of a basic hybridisation with the battery, the 100 MW battery can provide up to 100 MW of upward or downward aFRR depending on its setpoint and the state of charge. Besides each of the two variable speed hydro units can provide up to 100 MW of upward or downward depending on their setpoint while turbinating and a maximum of 33 MW while pumping.

In the case of the advanced Energy Management System (XOR technology), besides the previous performance, the combination of the two can provide up to 220 MW of upward aFRR from the 0 MW hydro setpoint. They can also provide 220 MW of combined upward and downward aFRR from most hydro setpoints.

In this scenario, the multi-market optimisation for 2030 shows that, under the basic hybridisation approach, the battery is mainly utilised for spot market arbitrage, selling roughly 145 GWh while consuming about 180 GWh. Simultaneously, it delivers upward and downward aFRR for slightly under 7,000 operating hours, corresponding to approximately 400 GW·h of aFRR (Figure 1 and Figure 2). This translates into an additional annual revenue of around €24 million thanks to the battery, yielding an estimated payback period of about three years for the battery investment.

By contrast, the optimisation with the advanced Energy Management System (XOR technology) notably reduces battery arbitrage (about 95 GWh sold and 115 GWh consumed) in order to provide aFRR during XOR mode. This occurs both when the hydro units are offline (0 MW) for approximately 2,900 hours per year and during roughly 850 hours when the hydro units are active on the spot market (Figure 1). Consequently, the Čierny Váh power plant contributes an additional 130 GW·h of aFRR capacity to the system (Figure 2), generating an extra €10 million in revenue relative to the basic hybridisation case, lowering the payback time of the battery to 2 years.

The schedule simulation results are even more pronounced than those reported in section 3.1, as the XOR mode is now far more frequently activated in the case of the advanced hybridisation (see Figure 1 in section 4), thereby providing substantially more aFRR to the system, as already outlined. Specifically, the number of starts and stops of the two hydro units rises from an average of about five per day for the basic hybridisation to more than thirty per day under the advanced Energy Management System solution, driven by the need to recharge the battery. Both solutions, however, still exhibit roughly two equivalent battery cycles per day on average. Moreover, the battery state of charge and the aFRR imbalances are much better controlled with the advanced hybridisation, benefitting from longer operation in XOR mode: aFRR imbalances are reduced by a factor of ten, while occurrences of battery state of charge exceeding 90% or falling below 10% are reduced by more than four. These deviations continue to arise primarily during periods when XOR mode is inactive in the advanced Energy Management System solution.

### **3.3. 125 MW / 250 MWh battery**

Finally, the addition of a 125 MW / 250 MWh battery to the Čierny Váh hydropower scheme was assessed in this study but only in combination with the advanced Energy Management System (XOR technology).

In this case the battery and the two variable speed units controlled adequately together can provide up to 256 MW of upward aFRR from the 0 MW hydro setpoint. They can also provide 256 MW of combined upward and downward aFRR from most hydro setpoints.

In this scenario, the study focuses solely on the advanced XOR control strategy. As expected, the larger battery enables increased spot market arbitrage, selling approximately 130 GWh while consuming around 150 GWh. Regarding aFRR, the schedule simulation closely resembles that presented in section 3.2, with provision in XOR mode both during periods when the hydro units are offline (0 MW) for roughly 3,500 hours per year and for about

170 hours when the hydro units are active on the spot market (Figure 1). The combined contribution of the two modernised hydro units and the battery delivers a similar total aFRR as in the advanced Energy Management System case of section 3.2, amounting to approximately 790 GW·h of aFRR (Figure 2). This results in an additional annual revenue of around €39 million from the battery, implying an estimated payback period of about three years.

With the larger battery, schedule simulations indicate similar hydro unit operation as XOR mode is about as frequently activated in the case of the advanced hybridisation than with the 100MW/200MWh battery of section 3.2 (see Figure 1 in section 4). Hydro units average thirty-five starts and stops per day, and battery still cycling of about two equivalent cycles per day, consistent with section 3.2. Figures regarding state-of-charge management, and aFRR imbalances also remain stable compared to those of the advanced Energy Management System solution of section 3.2.

#### 4. Conclusions

The analysis of these three hybridisation options demonstrates that battery integration at the Čierny Váh power plant offers substantial economic and technical benefits. In all scenarios, the battery contributes significantly to spot market arbitrage and, more importantly, to the provision of aFRR, with consistently about 7000 hours of aFRR provision (Figure 1).

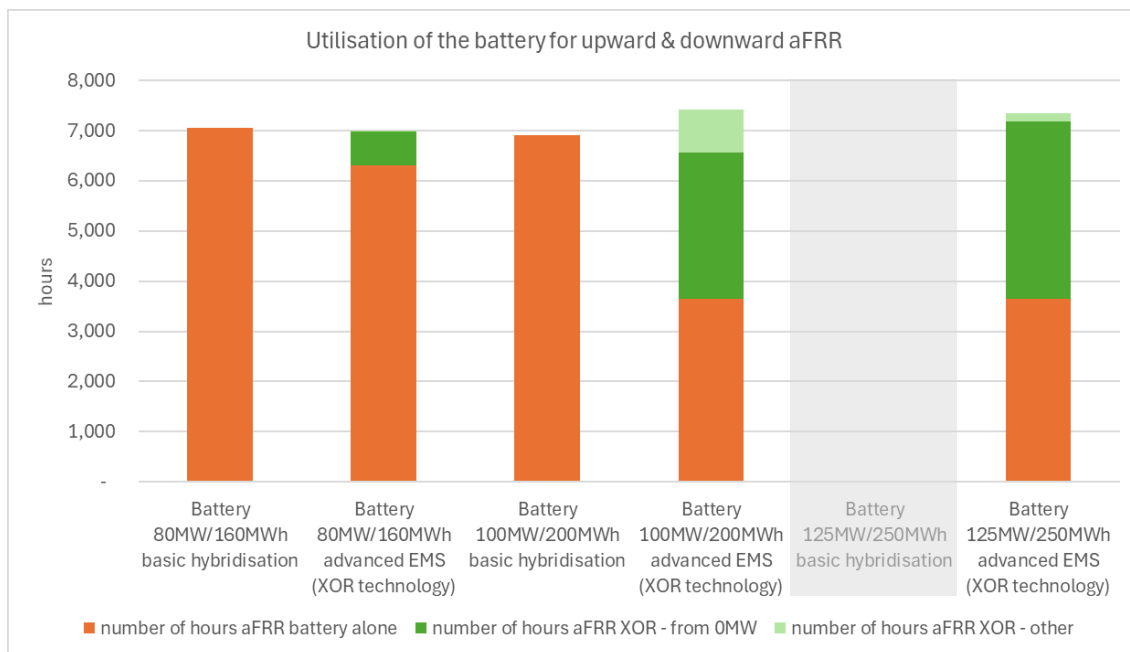


Figure 1: Utilisation of the battery for aFRR - multi-market placement optimisation of Čierny Váh 2030 (basic hybridisation with a 125MW/250MWh battery was not studied)

The economic impact is substantial: even under the basic hybridisation case, the battery generates additional annual revenues in the range of €20 million to €40 million<sup>2</sup>, with payback periods on the order of just a few years. The advanced Energy Management System considered (SuperGrid Institute XOR technology), further enhance these revenues by increasing aFRR provision (Figure 2), in particular taking advantage of the hydro units while they are at 0 MW setpoint (Figure 1). This control strategy upgrade allows to increase the annual revenues of the powerplant by €4 million to €10 million compared to the basic hybridisation.

<sup>2</sup> The revenue figures presented are based on a simulation study using a broad set of realistic assumptions and illustrate the strong economic potential of pumped storage–battery hybridisation. However, these simulations do not fully incorporate the technical conditions for BESS-based aFRR provision as defined by the Slovak TSO at the time of their publication (September 2025), which prevented their inclusion in this analysis. These conditions will be addressed in detail by further analysis, with revenue estimates being updated to provide a robust and realistic basis for the final investment decision on the battery and hybridisation components of the SE Integrator project.

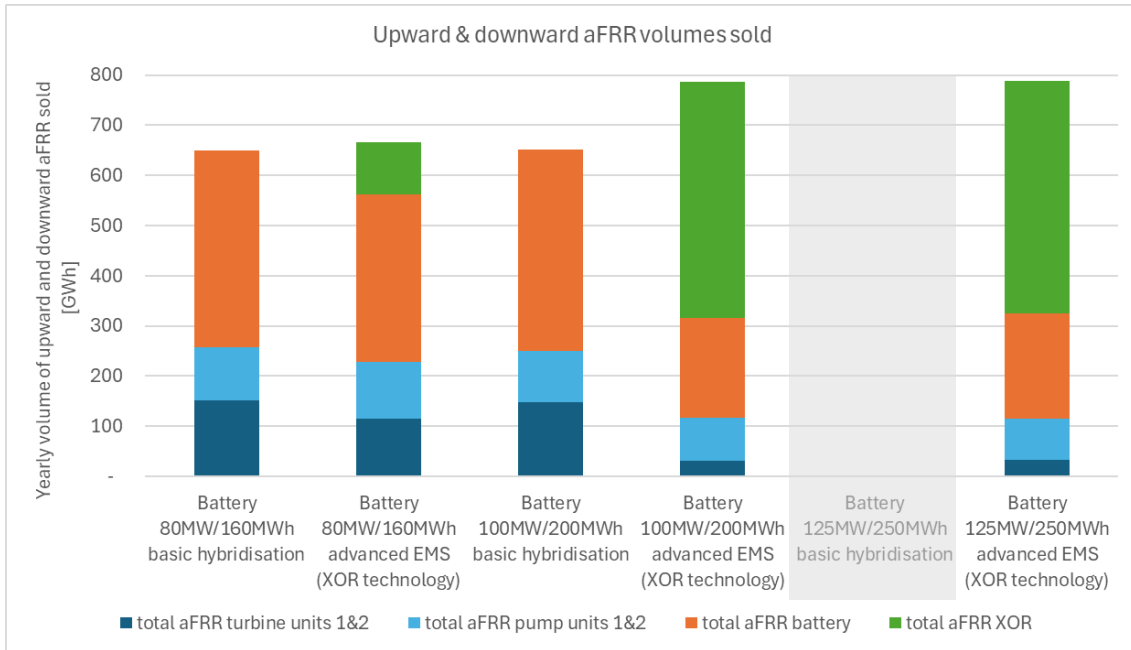


Figure 2: Volumes of aFRR sold - multi-market placement optimisation of Čierny Váh 2030 (basic hybridisation with a 125MW/250MWh battery was not studied)

Increasing battery capacity consistently improves both economic and technical indicators. Larger batteries enable higher spot market participation and greater provision of aFRR, leading to increased revenues while simultaneously improving the management of the battery's state of charge and reducing operational imbalances. Across all cases, the advanced Energy Management System ensures that aFRR revenue are maximised while imbalances are minimised, demonstrating that this advanced control strategy is critical to realising the full potential of hybridised hydro-battery systems.

Overall, the results show that battery deployment at the Čierny Váh power plant is highly profitable. Large volumes of aFRR provision, both within Slovakia and through interconnections, represent a reliable revenue stream. Moreover, it appears that larger batteries (100MW/200MWh or 125MW/250MWh options) together with the SuperGrid Institute's advanced control technology synergistically maximise both economic returns and operational indicators. These findings highlight that investments in battery hybridisation, when appropriately sized and controlled, constitute a robust strategy for enhancing the flexibility and profitability of the Čierny Váh and other hydropower plants in the future.

## **The Authors**

**Quentin BOUCHER** has been leading the electricity market economics' activity of SuperGrid Institute since 2019. Prior to this, he has worked during 8 years in the Transmission business where he led the implementation of Asset Management practices (ISO 55000) in both New Zealand and Colombia's TSOs. He also worked as Senior Asset Management Consultant for the South American branch of a UK based consultancy specialized in supporting the improvement of energy utilities' operations. Quentin is an engineer by training, he graduated from both École Polytechnique (France) and EPFL (Switzerland).

**Tomáš ŠIMOVIČ** is currently leading the business development team at Slovenske elektrarne. After joining Slovenske elektrarne in 2019 he worked as a Senior Quantitative Analyst at the Trading department and subsequently led the quantitative teams focused on asset backed trading. Prior to this, he was a senior analyst supporting prop and portfolio trading at SPP. He also spent 7 years at EDF R&D where he worked on mathematical optimization models and risk management and valuation. He is a graduate of the Czech Technical University in Prague, with an MSc. in technical cybernetics, and Ecole Nationale Supérieure de Techniques Avancées (ENSTA) in Paris.

**Fabien GRAND PERRET** is a specialist in energy system modelling, with a particular interest in the hybridization of hydroelectric power plants. Prior to his current position at SuperGrid Institute, he spent 15 years at EDF, where he worked on improving control systems and ancillary services provided to the Grid. He also has experience in plant commissioning. Fabien Grand Perret is a graduate of ENSMM.