Electricité de France Hydro’s overview of the First Israeli Hydro-Electric Pumped Storage Power Plant: GILBOA PSPP

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Abstract. The Israeli Public Utilities Authority (PUA) has decided to increase the instantaneous power available on the grid by adding Pumped Storage Power Plants (PSPP) to the existing generation capacity. PSP Investments Ltd. is a private investor that has decided to develop the GILBOA PSPP. The capacity of the GILBOA PSPP is 300MW (2x 150 MWe). The project performance has to comply with PUA regulation for PSPP, and with all relevant Israeli laws and standards. The GILBOA PSPP is located at the Gilboa Mountain, in the north of Israel, near the town of Beit She’an (about 120 km North of Tel Aviv). As during IAHR 2016, EDF Hydro presented different items from feasibility studies to installations on site including model tests and manufacturing process. This current paper will give an overview of the GILBOA PSPP through short descriptions of EDF Hydro feedback during the end of the installation, during commissioning and during meetings for preparation of acceptance tests with Israeli Electric Company. The main equipment from the 2 units (reversible Francis pumps-turbines, motor-generators and associated auxiliaries) to the hydraulic gates as well as units control and protection systems are provided by GE Renewable Energy which will also ensure Operating and Maintenance of the PSPP. GE Renewable Energy has introduced several technical innovations that will be presented in this paper as for instance, a dedicated trolley for the installation and the maintenance of the main inlet valves, or the thrust bearing with composite material PolyPad\textsuperscript{TM}. The GILBOA PSPP is capable of connecting on IECo grid in approximately one minute.
1. Introduction

Pumped Storage Power Plant (PSPP) are well-established in their ability to balance intermittent sources of renewable energy. In addition, they can also provide many stabilizing features to the grid. As a result of these and other benefits, many companies in the world are developing new PSPP. The Figure 1 presents the fixed speed and closed loop of PSPP under construction all over the world until October 2019 [1]. It is noticed that China has been launching a large plan of PSPP construction with large output per plant (e.g. Xinjiang Hami Tianshan 1200 MWe, Yunxia 1800 MWe and Yanginag 2400 MWe). Depending on the market of electricity, European countries have decided either to develop new PSPP project as in Switzerland (Lagobianca 1000 MWe) or in Russia (Zagorsk II 840 MWe) or to postpone PSPP project as in Germany (Waldeck II+ 300 MWe). And finally in the rest of the world, some countries have been developing PSPP project as for instance in India (Tehri 1000 MWe), in Indonesia (Upper Cisokan 1040 MWe) and in Israel (Gilboa 300 MWe and Kokhav Hayarden 340 MWe). The present paper is specifically focused on the Gilboa Project, the first Israeli PSPP.

![Figure 1: Fixed speed and closed loop PSPP under construction in the world in October 2019 [1].](image)

The Gilboa PSPP is located at the Gilboa Mountain, on the North of Israel; close to the town of Beit She'an, about 120 km to the North from Tel Aviv. The 300 MWe Gilboa PSPP, as shown in Figure 2 consists of:

- An upper reservoir of 2.4 Mm³ water;
- A High Pressure HP vertical shaft;
- An horizontal HP waterway tunnel and a steel lined bifurcation to feed the two penstocks;
- An Underground Power House composed of two caverns, see Figure 3:
  - one cavern housing the two Pump-Turbines and generator-motors, the Main Inlet Valves and associated equipment;
  - one cavern housing the two main power transformers and the common starting equipment (Static Frequency Converter and associated equipment);
- A low pressure LP waterway tunnel with a 70m height surge shaft;
- A lower reservoir of 2.4 Mm³ water;
- A 161 kV outdoor substation for connection to the Israel Electric Corporation (IEC) grid and operating buildings, one next to the substation, the other one as main operating building, also designed to welcome visitors.
The design and erection of both reservoirs were realized by an Israeli company, Avidan. The Underground Power House, surge shaft and tunnels were erected by a Korean company, Kyungdong and finalized by Pemko Shura. All unit components and Electro-Mechanical equipment were supplied by GE Renewable Energy. All the contractors and sub-contractors of the project were well orchestrated by Electra Agira Sheuwa, the Engineering Procurement & Construction company (EPC) with the technical support of the Hydraulic Engineering Center of Electricité de France, EDF HYDRO-CIH [2].

GE Renewable Energy introduced several technological innovations when installing equipment of Gilboa PSPP:
- a dedicated trolley for the installation and the maintenance of the main inlet valves,
- independent servomotors for guide vanes operating,
- thrust bearings with composite surfaced material Polypad™,
- Glass Fiber Reinforced Plastic pipes for drainage and dewatering system,
- Innovative use of auxiliary equipment and control algorithms for optimized start-up in turbine mode.

EPC emphasized some innovations too:
- Transportation and installation of main transformers without civil work disturbances,
- Drying high voltage connectors between 161 kV cables and main transformers,
- Carpi membranes inside the high pressure shaft and the high pressure tunnel,
- Surge shaft design taking into account both upward and downward head losses.
2. Innovation

2.1. Carpi membranes

The High Pressure waterway comprises a nearly 500 m high vertical shaft with 4.5 m diameter. In 2017 Carpi had already performed repair works in the concrete intake structures of the two reservoirs, lined with a white HDPE membrane. Then, PSP Investments Ltd, owner of the plant, has requested Carpi to provide a detailed design for the waterproofing of the High Pressure shaft with an exposed geomembrane sealing system, with the goal of significantly reducing the potential leakage through the concrete lining and mitigating the loss of valuable water in the High Pressure waterway.

The geomembrane sealing system consists of an exposed PVC geocomposite installed on the surface of the concrete lining and fastened by means of stainless steel flat profiles [3]. The waterproofing liner was installed all along the total height of the HP shaft and on the full-round of the shaft cross-section, from approximately El. +389 m to the beginning of the transition protected with a metal lining at El. -86.5 m (just above the bottom elbow), as well as on horizontal concreted part of the horizontal High Pressure tunnel (covered length is approximately 376 m). The total surface of the Carpi waterproofing liner has been estimated in approximately 3900 m².

It comprises the following main elements:

- Waterproofing polymer liner, consisting of a SIBELON® PVC geocomposite, i.e. a SIBELON® PVC geomembrane heat-bonded during fabrication to a non-woven, needle punched, polypropylene geotextile;
- Anchorage system, consisting of vertical lines of stainless steel flat profiles AISI 316, fastened to the concrete lining with mechanical anchors of high resistance. The design of the anchorage system allows to resist the forces generated by the water flow and to provide a pre-tensioning of the waterproofing liner, with the aim of mitigating the formation of folds and wrinkles, which may be detrimental to the durability of the system;
- Perimeter seal, consisting of transversal (horizontal) stainless steel flat profiles AISI 316, fastened with mechanical anchors of high resistance and sealed with epoxy resin and rubber gasket. The system is designed to withstand a high pressure head and has been successfully tested in a pressure chamber under 800 m WC (water column).

In the remote occurrence of an accidental damage, the geocomposite SIBELON® CNT 4400 can be repaired easily and quickly by applying heat-seamed patches made of geomembrane SIBELON® C 3900 or by replacing an entire section by installing new sheets of geocomposite. The perimeter seal and the anchorage system can be dismantled and re-used.

Figure 4: Carpi membrane in the High Pressure shaft and tunnel.
2.2. Surge shaft design
As part of the overall Gilboa project, EPC requested EDF Hydro Engineering Center for the design of the orifice of the tail race surge shaft.

The surge shaft located at the Low Pressure Tunnel of Gilboa hydropower plant was an effective measure to protect the headrace tunnel against high pressure fluctuations. It reflected the transient pressure waves that are generated by the variation of the flow discharge inside the powerhouse. The up- and down-surges inside the tank, as well, as the percentage of the transmitted pressure waves towards the head race tunnel are significantly affected by the local hydraulic losses situated at the entrance of the tank. The purpose of the circular orifice diaphragm defined at the bottom of the surge shaft is to generate such a local head loss by contracting the flow inside the connection tunnel between the surge tank and the head race tunnel. The diameter of the orifice was an important parameter to adjust in order to fulfill the hydraulic design criteria of the project. The value of the interior diameter of this thin steel orifice was determined by using analytical formulations by taking into account the head loss coefficient in both flow directions from and towards the surge shaft [4]. Thanks to EDF-CIH experiences, an uncertainty prediction was provided between the proposed geometry of the orifice diaphragm and the real value of head loss coefficients.

2.2.1. Gardel’s model

Figure 5: Gardel’s configuration.

\[ R_s = \left[ \frac{1}{1 - \left( \frac{3}{2} \alpha - \alpha^{3/2} \right) \left( 1 - \psi^2 \right)} - \psi \right]^2 \left( \frac{V_s^2}{2g} = \frac{\psi_s^2}{2g} = KQ_s^2 \right) \]

Then the coefficient \( K \) of head losses is deduced from equation (1) and is defined by the relation (2) as

\[ K = \left[ \frac{1}{1 - \left( \frac{3}{2} \alpha - \alpha^{3/2} \right) \left( 1 - \psi^2 \right)} - \psi \right]^2 \left( \frac{1}{2gS_0} \right) \]

with \( \alpha = \frac{\delta}{360} \), \( \varphi = \frac{\phi}{d} \), \( \psi = \frac{\phi}{D} \)

and \( S_0 = \pi \left( \frac{\phi}{2} \right)^2 \)

If the flow is going up from the tail race and to the surge shaft, \( K = K_u \) is defined by relation (2)
If the flow is going down from the surge shaft to the tail race, some parameters change and \( K = K_d \) is defined by relation (3)
2.2.2. Gilboa tail race surge shaft

The surge shaft orifice was located close to the LP tunnel junction.

\[
K = \left[ 1 - \frac{3}{2} \alpha - \alpha^{3/2} \left( 1 - \phi^2 \right) \right]^{-\frac{1}{2}} \frac{1}{2g S_0^2}
\]

with \( \alpha = \frac{\delta}{360} \), \( \phi = \frac{\phi}{D} \), \( \psi = \frac{\psi}{D} \)

and \( S_0 = \delta \left( \frac{\phi^2}{2} \right) \) (3)

\[
\frac{d}{D} = 5 \text{ [m]}
\]
then \( \phi = \psi \) (4)

The values of surge shaft head-losses coefficients given by GE Renewable Energy are:

From tail race to surge shaft: \( K_d = 1.30 \times 10^{-3} \left[ \frac{m}{(m^3/s)^{1/2}} \right] \) (5)

From surge shaft to tail race: \( K_d = 9.63 \times 10^{-4} \left[ \frac{m}{(m^3/s)^{1/2}} \right] \)

Considering the relations (2), (3), (4) and (5), a system of two non-linear equations with two unknowns \((\delta, \phi)\) was solved as:

\[
\begin{bmatrix}
1.30 \times 10^{-3} \\
9.63 \times 10^{-4}
\end{bmatrix}
\begin{bmatrix}
\frac{1}{1 - \left( \frac{3}{2} \frac{\delta}{360} - \frac{\phi}{360} \right) \left( 1 - \frac{\phi^2}{2} \right) - \frac{\phi}{D}} \\
\frac{1}{1 - \left( \frac{3}{2} \frac{\delta}{360} - \frac{\phi}{360} \right) \left( 1 - \frac{\phi^2}{2} \right) - \frac{\phi}{D}}
\end{bmatrix}
\begin{bmatrix}
\frac{\phi}{D} \\
\frac{\phi}{D}
\end{bmatrix}
= 0
\]

(6)

From this system, the diameter \( \phi \) of the orifice and the geometrical angle \( \delta \) are defined.

The Thickness of the orifice is defined by
\[
\tan \beta = \tan \left(\frac{180^\circ - \delta'}{2}\right) = \frac{e}{d - \phi}
\]
\[
e = \frac{d - \phi}{2} \tan \left(\frac{180^\circ - \delta'}{2}\right)
\]

The main parameters for the design of this orifice are summarized in the Table 1.

| $\delta'$ [°] | d [m] | $\phi$ [m] | $\beta$ [°] | e [m] |
|---------------|-------|-------------|-------------|------|
| 144.40        | 5.00  | 3.10        | 17.80       | 0.305|

Table 1: Parameters of the surge shaft orifice.

2.3. Main Inlet Valve trolley
The main function of the Main Inlet Valve Trolley consists of moving the Main Inlet Valve from the unique main shaft hole in the power house to its final position and vice-versa if maintenance operation required. It was specifically designed and built by GE Renewable Energy for Gilboa PSPP (Figure 7). The trolley is welded and bolted with the following dimensions 6000 x 2550 x 2800 mm. It finally weighed 4,8 t.

Figure 7: Main Inlet Valve Trolley.

2.4. Independent servomotors
The distributor mechanism, which adjusts the inlet flow discharge, consists of 20 independent servomotors instead of an operating ring. They offer large flexibility on mechanism operating in order to fulfil with mode change time request and potential need for desynchronizing to stabilize the unit during speed-no load operation.

Figure 8: Distributor.
2.5. **Polypad™ thrust bearing**

In the past, manufacturers had used the polymer PTFE, Poly Fluoro Ethylene until 1980. Therewith, higher loads and a better temperature resistance can be realized compared to babbit coating. Most often PTFE was used. The Japan firm Daido Metal Co., developed a pad coating with the material PEEK (Poly Ether Ether Ketone) with a high load capacity and a good material behavior. PEEK’s yield strength and melting point are higher than they are for PTFE. GE Renewable Energy has extensively tested such pads and supplied PEEK-based polymeric pads, called Polypad™, instead of using white metal or babbit, see Table 2 [5-7].

GE Renewable Energy performed a comparison of losses reduction of thrust bearings between white metal (red curve, Figure 9) and Polypad™ (blue curve) versus the diameter of the thrust bearings. Figure 9 shows a reduction of losses by using Polypad™ compared to white metal.

| Property                          | Polypad™ | White Metal |
|-----------------------------------|----------|-------------|
| Yield strength at 20,100,250°C    | 240, 150, 50 [MPa] | Density 1430 [kg.m⁻³] |
| Elongation                        | 2%       | Thermal conductivity 0.4 [W.m⁻²K⁻¹] |
| Thermal expansion MD, TD          | 0.9, 4.2x10⁻⁵ [K⁻¹] | Friction coefficient 0.1 |
| Wear resistance acc. babbit       | 10 times | Melting point 341 [°C] |
| Creep resistance acc. babbit      | 10 times | Stability temperature 328 [°C] |

Table 2: Coating material data for Polypad™.

![Figure 9: Study showing potential power loss savings for hydro generator thrust bearings.](image)

![Figure 10: View of Gilboa thrust bearings with Polypad™.](image)

The Figure 10 shows a Gilboa thrust bearing with Polypad™. In the middle of the pad, there is the oil injection chamber (in grey) and a copper implant for a good sealing. Then, along the outer diameter, two orifices for temperature probes are designed to measure the temperature of the oil film and not of the metal.
GE Renewable Energy performed finite elements calculation to simulate the distribution of temperature of one Polypad™ thrust bearing for three operating points. (Table 3):

- Case 1: Continuous operating point at rated speed;
- Case 2: Load intake: machine start;
- Case 3: Runaway condition in turbine mode.

In the Figure 11 and from Table 3, it is noticed that it is allowed to have a thin oil film gap by using polymer pad. This behavior is the resulting effect of the thermal shield of the polymer composite. Then, it strongly reduces the gradient of temperature of the thrust bearing and so the corresponding deformations.

| Case 1 | Case 2 | Case 3 |
|--------|--------|--------|
| Load [kN] | 2330   | 4120   |
| Polypad mean pressure [MPa] | 3.76   | 6.66   |
| Cold oil temperature [°C] | 39     |        |
| Minimum oil film gap [mm] | 0.0352 | 0.0162 | 0.0212 |
| Power loss [kW] | 166    | 164.1  | 295.8  |
| Temperature of the Polypad thrust bearing [°C] | 94.5   | 108.7  | 109.6  |

Table 3: Temperature of Gilboa Polypad™ thrust bearing.

![Figure 11: Polypad™ thrust bearing temperature.](image)

![Figure 12: Polypad™ thrust bearing oil pressure.](image)
Furthermore, in case 2 and 3 and for a load rejection in pump mode the maximal temperature of the oil film could reach 120°C without any damage for the thrust bearing. Moreover, the 2 temperatures sensors measure either a cold or hot temperature depending if generating mode or pumping mode.

2.6. GRP pipes for drainage, dewatering and cooling systems
GE Renewable Energy installed glass fiber reinforced pipes, GRP from Fiberdur manufacturer, instead of stainless steel pipes for drainage, dewatering and cooling systems. GRP pipes have proven to be corrosion free, maintenance free, fire resistant and low weight. They could be used allowing a pressure resistant up to 6 bars. The jointing method is bonding connection. The installation of GRP pipes systems leads to considerable cost savings if specific workers are skilled. In refurbishment projects the cost for installation can be reduced considerably in comparison with traditional materials.

2.7. Turbine booster

2.7.1. Optimizing start-up sequence
Improvement of transient sequences may increase the demands on the hydraulic machine. To ensure its reliability under the new operating regime and faster mode changes, the experimental characterization of the Gilboa pump-turbine has been performed by GE Renewable Energy, [8]. This includes a development test on a specific reduced scale model turbine, as well as in-situ tests in a real power-station. This unique testing plan on both model and prototype, allows the validation of the scaling of complex dynamic phenomena involved in transient sequences such as fast start-up or mode change over from pump to turbine operation.
Gilboa’s “normal” start-up including load taking takes approximately 60 seconds to go from Standstill state to 100% power in generating mode, while a “fast” start-up is even quicker. The Figure 15 shows an example of trajectory in turbine mode after the first step of sequences optimization in the control
system. The guide vane trajectory (opening law) is smoother than on a conventional start-up with a two
slope law and avoid unnecessary pressure fluctuations.

![Graph](image)

Figure 15: Gilboa optimization start-up in turbine mode (simulations).

(red: rotation speed, green: guide vane opening) [7].

During the commissioning, the runner of the Unit 1 is equipped with strain gauges to evaluate
mechanical efforts applied on it during fast start. Those measurements help to optimize start parameters
to avoid mechanical damages of the runner.

2.7.2. Sequence booster technology
In order to obtain start-up times and transition times which are faster than the “normal” sequences,
auxiliary equipment (SFC) and intelligent control algorithms have been applied. This booster has the
added benefits of offering a better stabilization of unit speed (notably preventing speed overshoot) and
of securing the task of unit synchronization. It has been tested and proven during commissioning.

2.8. Clean installation of main transformers
The installation of Gilboa main transformers followed a non-conventional way but very clean and
without any damage of the civil work. Usually, two metallic rails are embedded in the concrete floor.
Here, EPC used a specific transport truck, two temporary rails fitted within Teflon pads, a strong
hydraulic jack and human energy, see Figure 16 and Figure 17.

![Images](image)

Figure 16: a) Transportation of Gilboa main transformer, b) Rails with Teflon pads.
3. Unexpected technical events

3.1. Braking issues
During commissioning step, two unexpected braking action happen on the same unit. One due to a human error and one due to a conflict with two simultaneous control system orders during a start-up, caused by undue operation of the creeping detection sequence. Then, the braking disk was burnt twice when brakes were applied after emergency shut down at high speed. Because flatness of the surface of the braking disk was affected due to both events and blue spots were observed, the damaged brake disk was replaced by a new one as well as callipers, too. The Figure 18 presents damages on braking disk surface and fire inside the generator head cover.

3.2. Main transformer Unit 1 fire issues
On March 5, 2019, at 01:56, the Gilboa Unit 1 transformer tripped under differential protection activation. The transformer was energized but unloaded, generator unit 1 was out of service. Fire alarm was activated. Fire brigade arrived on site and extinguished the flames.
Failure scenario involves L3 cable head and its epoxy socket housing. The most likely root cause is the cable laying and lack of support which allows the bending force of the cable to be applied through the cable head to the silicon insulator (Prysmian click-Fit connector) and in turn to the epoxy socket:
- Cable was pushing side way against the epoxy socket and cable head,
- The silicon rubber insulator was compressed asymmetrically leaving small air pocket along the silicon/epoxy interface,
- Partial discharges occurred along the silicon rubber and damage the silicon insulator till breakthrough
- Epoxy socket might also have been cracked by the cable bending force creating a weak point on the epoxy casting. Through that crack line voltage went to ground.
- The arc flew from line cable to tank along the epoxy inner cone, and melted part of the steel ring at the bottom of the cone.
- During the fault development, which generated an energy around 2MJ, the air pressure in the cable socket increased till it ruptured and fell in the transformer.
- As the socket detached from the cable end, the connection ring and top connection of socket started to separate creating an arc and molten copper + aluminium.
- Falling debris into the transformer include epoxy socket debris, molten metal, but also carbon loaded silicon which were vaporized by the fault energy and sprayed in the transformer oil; this contaminated the whole oil load with carbon particles.
- As the oil pump kept running after the fault, the fallen particles were spread to many locations inside the transformer.
- Also during pressure build up in the cable junction, the fiber optic plastic storage box was ejected by hot gazes and fallen to the ground.
- Ground being moistened with oil spill coming from a leaking tap, the burning plastic box ignited the oil on the floor.
- Let’s note that under such an electrical fault, and in the absence of tank rupture, a fire burst is very unlikely; however in the very case of Gilboa Transformer Unit 1, the triangle of fire was fulfilled due to: i/ fuel: oil on the ground, ii/ oxygen: in the cell air, iii/ heat: flaming plastic box ejected from the cable end.
- The oil being located solely on the High Voltage side of the transformer, the fire only burnt in that place.
- The area of High Voltage side was damaged, including the neutral cable lead coming down from neutral bushing, which cable insulation melted up to about 1.5 m height.
- The fire detection in the room was activated.

Moreover, Prysmian, the manufacturer of the “Click-fit” connector, after failure analysis insists that the clickers on transformer side epoxy cone were not properly engaged into the silicon insulator groove. The clicker on transformer side connection fits in a half moon shaped groove (which helps extract the silicon insulator if need be, by rotating the silicon insulator 90°). In Prysmian analysis, it is mentioned that the clickers were found in the retracted position leading to the conclusion that the silicon insulator was not positioned correctly and that the clickers never jumped out. When checking on the drawings, the silicon insulator versus epoxy cone angle tolerance, it was found that +/-40° error would still lead to the clickers expanding out and locking in position. If the relative angular position of silicon insulator versus epoxy cone is more than +/- 40° then the clickers do not expand fully outward. In Prysmian’s report, the angular position error is assumed to be 75 to 80° (90°-10°/15°), meaning that the clickers were slightly out but not fully. It is very unlikely that the silicon insulator was not at least slightly clamped by the clickers; otherwise, the silicon insulator would not be pressed correctly against the epoxy cone and air bubbles would have remained causing Partial Discharge and leading to failure under high voltage test. The clickers might have been slightly out but not enough to resist the full thrust during fault.

This leads to the conclusion that silicon mounting in transformer side socket was not done as per the specifications (angular position), but that it was at least slightly clamped so that the 2 conic shapes (silicon and epoxy) were still enough pressed against each other.

As a consequence in order to resume service, the transformer was rewound because of its internal pollution with conductive debris, and cable trays were installed to better lead the High Voltage cable in the transformer cable box.
4. Conclusion
The private 300MWe Gilboa PSPP is the first Israeli Hydro-Electric Pumped Storage Power Plant in Israel. The handing over is scheduled in February 2020.
This is an innovative project due to the fact that in Israel there is no any previous installed and generating large scale hydraulic power plant. This paper briefly presented the innovative solutions and tools successfully implemented or used in the frame of Gilboa project.
It is important to emphasize that both Gilboa EPC members and Owner members have been involved for the first time in a hydroelectric project from the “white page” to the operating step. They have learned hard, they have been applying better and better the advices from all their consultants and brought innovative solutions. Finally, going over their own comfort and far beyond their initial knowledge, they succeeded in achieving an amazing project.
5. References

[1] IHA's Hydropower Pumped Storage Tracking Tool, https://www.hydropower.org/hydropower-pumped-storage-tool.

[2] P. Maruzewski, T. Sautereau, Y. Sapir, H. Barak, F. Hénard, J.-C. Blaix, “The First Israeli Hydro-Electric Pumped Storage Power Plant Gilboa PSPP”, IAHR, 2016, Grenoble.

[3] Carpi, “Lining of the high pressure shaft with carpi exposed geomembrane sealing system”, Gilboa Technical Report.

[4] Gardel A., “Chambres d’équilibre, Analyse de quelques hypothèses usuelles. Méthodes de calcul rapide”, Thèse EPFL N°32, 1956, Lausanne.

[5] A. Schubert & T. Brescianini, “Application d’une butée revêtue de PEEK à l’occasion d’une réhabilitation d’une grande centrale hydroélectrique avec une augmentation de charge en parallèle”, Alstom Hydro Birr, 10ième EDF/Prime Workshop, Futurscope, Poitiers, 6-7 Octobre 2011.

[6] P. Pajaczkowski & A. Schubert, “Alstom study shows PEEK coated PolyPad™ bearing pads reduce power losses by up to 30%”, Alstom Hydro Birr, HydroPower, Italy, 2014.

[7] M. Luu-Dinh, “Bearings calculation note”, Gilboa Technical Report H-80600MKA31-SA30ED-02, GE Renewable Energy, 2015.

[8] A. André, Q. Alloin, S. Vintrou, G. D. Ciocan & P.-Y. Lowys, “On-line in Israel: Highly reactive pumped-storage for transition to renewables”, Proceedings Hydro 2019, 14-16 October 2019, Porto.

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