Seawater pumped storage, from theory to practice: An Italian case study

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Introduction

The need for decarbonization has created a strong incentive for development of renewable sources (mainly wind and solar) that are inherently intermittent and non-programmable; it consequently, it has become crucial to integrate adequate capacity for regulation services, particularly in regions with intrinsically weak high-voltage grid systems. In this context, Edison started to develop new hydroelectric pumped storage plants (PSP) in South Italy region; a preliminary design for several of these PSP has been completed, and the complex authorization process is underway.

Considering not only the needs of the national grid system but also the increasing attention on freshwater management in these entangled socio-environmental contexts strongly influenced by climate change, Edison has developed a marine pumped storage plant, called Favazzina. Nowadays, marine pumping systems are gaining significant attention due to the clear benefits of utilizing an essentially “infinite” resource. Although the advantages related to the construction of a small-volume basin, ,the managing of saltwater along with the addressing of the coastal morphodynamic processes at the intake, still presents technical challenges.

The main characteristics of Favazzina PSP plant are here summarized: i) ~600 m gross head; ii) 47 m^3/s of nominal flow; iii) ~ 255 MW in generation mode; iv) ~325 MW in pumping mode; v) 2 ternary units; vi) hydraulic short circuit (to obtain maximum operating flexibility).

In the present study the numerous technical challenges encountered during the design phase of the project span from the choice of the position of the upper basin, to its waterproofing systems and hydraulic design, through the arrangement of the underground waterways and the powerhouse cavern. Moreover the foreseen environmental mitigation measures, implemented to ensure minimum impact of the plant, are also highlighted within the distinctive natural context which the plant can be found, together with the specific technological characteristics of the adopted solutions. Finally, the document discusses the potential for replicating the solutions adopted and analyses the key challenges faced during the complex implementation of this large-scale project.

1 General framework of pumped storage in Italy

Currently, several pumped-storage power plants (PSPs) are operational in Italy, with a combined installed capacity of approximately 6.5 GW in pumping mode and 7.6 GW in generation mode. Among these, the six largest plants each exceed 500 MW in capacity, together contributing to a total of 5.3 GW.

The vast majority of these plants are located in North Italy region, with only a few exceptions situated in Central and Southern regions. The largest plants were built and commence operation between 1970s and early 1980s, in connection with the development of the Italian nuclear powerplants program. Due to the limited load-following capability of nuclear power plants, the surplus electricity generated during off-peak nighttime hours necessitates absorption through auxiliary demand management systems.

The construction of several large PSPs specifically aimed at addressing this issue by absorbing the excess of electricity production during off-peak periods and simultaneously matching energy demand during peak hours, effectively enabling energy time-shifting.

After a couple of decades of limited interest in PSPs and a steady decline in annual production from 8 to 2 TWh, PSPs have recently garnered renewed and increased attention due to the impacts on the electricity grid by the rapid and widespread integration of intermittent and non-programmable renewable energy sources (RES).

The renewed attention towards PSPs is reflected in the European (Union?) energy policy, implemented in Italy by the National Integrated Plan for Energy and Climate, with the latest update of June 2024 which keeps ambitious targets by 2030 for new storage capacity.

Despite the uncertainties associated with the length, duration, and complexity of authorization procedures, several operators and investors have initiated new pumped storage plant (PSP) projects in recent years.

Despite the uncertainties associated with the duration and complexity of the authorization procedures, several operators and investors have initiated new PSPs projects in recent years.

Table 1 shows the main features of the projects. With the sole exception of one project, all newly initiated pumped storage developments are geographically located in Central and Southern regions of Italy, including the main islands. The main reasons for such distribution are:

- these are the areas where the major future development of intermittent RES and the relevant overgeneration is expected;
- thus, these are the areas where future development will weaken the grid and will require new storage capacity and provision for suitable ancillary services;
- in these areas are located many large reservoirs, mainly built for irrigation and drinking purposes, which can serve as lower or upper reservoirs for the new project, thus reducing the global costs.
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Moreover, few Italian hydro plants operator, proposed the rearrangement of existing production plants adding to them pumped storage or only pumping facilities.

The following table deserves an additional comment. With so many projects entering the EIA procedures, only very few of them so far completed the environmental procedure and entered the next authorization step, making the Italian climate goals even harder to achieve.

N°	Plant	Type	Location	Operator	$P_{Turbine\ Mode}$ [MW]	$P_{Pump\ Mode}$ [MW]
1	Valcimarra II	Add PSP to hydro	Central Italy	Enel	19,2	31,5
2	Provvidenza II	Add PSP to hydro	Central Italy	Enel	202	194
3	San Giacomo III	Add pump to hydro	Central Italy	Enel		231,2
4	Cucchinadorza	Add PSP to hydro	Sardinia	Enel	41,5	40,6
5	Pizzone II	Add PSP to hydro	Central Italy	Enel	306	294
6	Guadalami	Uprating	Sicily	Enel	20,9	20,9
7	Favazzina	New PSP	Southern Italy	Edison	255	325
8	Taccu Sa Pruna	New PSP - existing lower reservoir	Sardinia	Edison	341,4	391,8
9	Pescopagano	New PSP - existing upper reservoir	Southern Italy	Edison	212	264
10	Villarosa	New PSP - existing lower reservoir	Sicily	Edison	270	285
11	Serra del Corvo	New PSP - existing lower reservoir	Southern Italy	Edison	300	400
12	Orichella	Exixting plant reactivation	Southern Italy	A2A	152	54
13	Campolattaro	New PSP - existing lower reservoir	Southern Italy	Rec	572	628
14	Gravina - Serra del Corvo	New PSP - existing lower reservoir	Southern Italy	Fri-el & al.	210	210
15	Mandra Moretta	New PSP	Southern Italy	Fri-el & al.	200	222
16	Rivalta	New PSP	Northern Italy	SKI W AE	154	170
17	Olai Cumbidanovu	NA	Sardinia	DHS	NA	NA
				TOTAL	***3256***	***3762***

Table 1 – Main features of the PSPs projects in Italy [1]

2 Favazzina main technical features

2.1 General description

Favazzina PSP has all the typical components of this type of power plants, which can be seen and resumed in Figure 1 and Table 2.

Parameter	Value	UoM	Parameter	Value	UoM
Exploitable upper reservoir volume	~ 1.100.000	m^3	Units centerline elevation	-60	m a.s.l.
Maximum allowed water level at the upper reservoir	631,37	m a.s.l.	Rated speed	500	rpm
Maximum normal regulation water level at the upper reservoir	631	m a.s.l.	Rated voltage	20	kV
Minimum normal regulation water level at the upper reservoir	615	m a.s.l.	Grid Frequency	50	Hz
Average sea water level	0	m a.s.l.	Rated flow of each unit - Turbine mode	23,5	m^3/s
Average gross head	~ 620	m	Rated flow of each unit - Pump mode	23,5	m^3/s
Minimum consecutive hours of generation at rated power	~ 8,0	h	Power factor	0,85	-
Minimum consecutive hours of operation at rated power - Turbine mode	~ 8,0	h	Rated power of each unit - Turbine mode	128	MW
Minimum consecutive hours of operation at rated power - Pump mode	~ 620	m	Rated power of each unit - Pump mode	163	MW
Average net head - Turbine mode	~ 610	m	Apparent power of the each motor-generator	200	MVA
Minimum net head - Turbine mode	~ 600	m	Total impounded volume	~ 1.200.000	m^3
Maximum net head - Pump mode	~ 650	m	Crest perimeter	1,370	m
Average net head - Pump mode	~ 640	m	Crest width	6	m
Minimum net head - Pump mode	~ 630	m	Wetted surface at min. regulation level	~ 43.000	m^2
Rated flow - Turbine mode	~ 47	m^3/s	Wetted surface at max. regulation level	~ 98.000	m^2
Rated flow - Pump mode	~ 47	m^3/s	Wetted surface at max. allowed level	~ 99.000	m^2
Rated output - Turbine mode	~ 255	MW	Maximum height (outer side)	25	m
Rated output - Pump mode	~ 325	MW	Maximum height (inner side)	20,8	m
Pressure tunnel diameter	4.200	mm	Bottom elevation	614,75	m a.s.l.
Penstock diameter	4.200	mm	Crest of dam elevation	633,30	m a.s.l.
Total length of the waterways	~ 5.000	m	Daily water level variation	15,95	m
Surge tank diameter	10	m	Freeboard	1,93	m
Surge tank height	70	m			

Table 2 – Main technical features

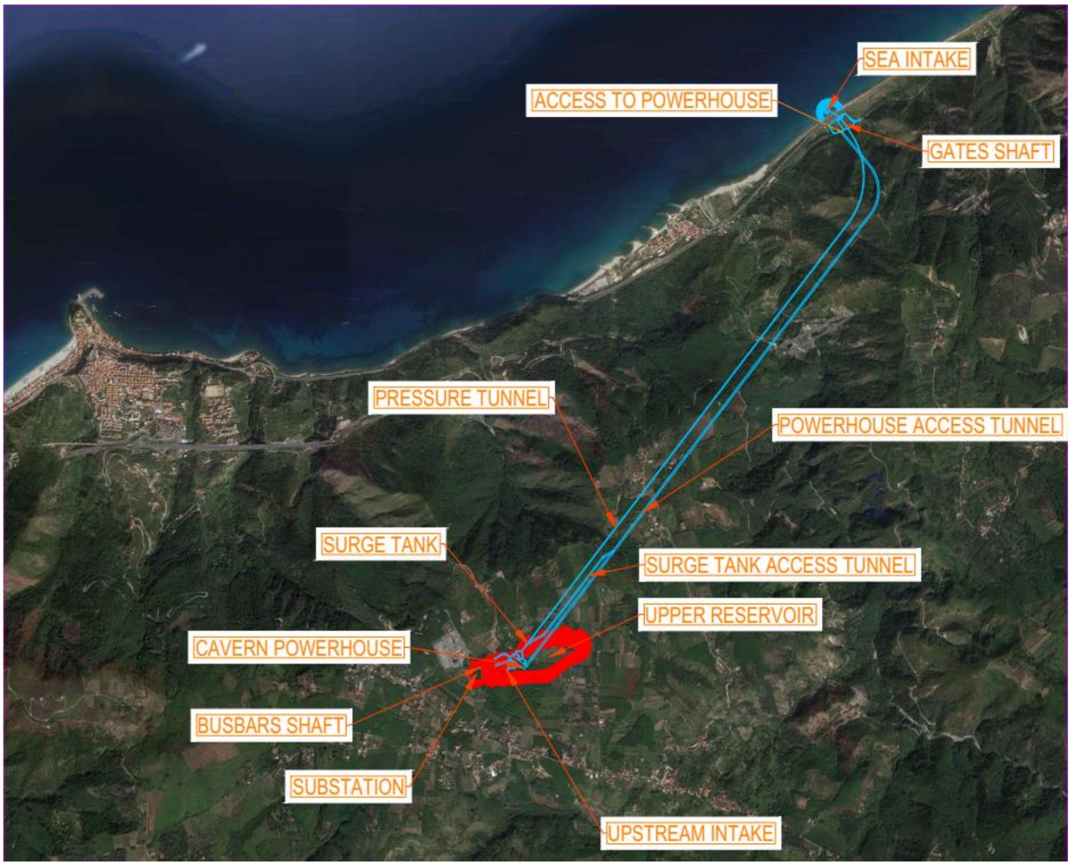

Figure 1 – Plant scheme

2.2 Sea intake

2.2.1 Constraints

Normally, the choice of the sea intake type is driven by the following constraints:

- to protect the intake structure from expected wave height to ensure its durability;
- to guarantee the intake rated flow of 47 m^3/s;
- to ensure a very low concentration of suspended sediment in the water in order to ensure the durability of the ternary units (pumps and turbines);
- to minimize interference with the longitudinal transport of marine sediments;
- to interdict (for safety reasons) access to vessels and people in the intake area;
- to ensure navigation safety in the surrounding area

Furthermore, considering the presence of the mouth of two streams near the intake structure, the planned protection structures had to be such as to:

i) not obstruct the outlet of these streams to the sea;
ii) not impact the hydraulic risk in the area;
iii) prevent the sediments transported by the watercourses from being sucked up by the intake structure;
iv) prevent the silting up of the intake structure.

2.2.2 Alternatives

To date, even though not in operation, the only pumping station powered by sea water is the one in Yanbaru, on the island of Okinawa in Japan, which includes an intake structure consisting of a basin along the coastline protected by a barrier of tetrapods. To explore further different design alternatives that could have been suitable for this case, other types of intakes, primarily used in desalination plants, were considered, , such as:

A. direct intake near the coast, achievable in sites that are naturally characterized by low-energy incident wave motion or artificially protected by defense structures.
B. direct intake in deep water, achievable either via a buried underwater pipeline (the most commonly used solution) or via a pipeline installed on a jetty or pier.

2.2.3 Final selected solution

The choice between the proposed design alternatives was made using a quantitative evaluation system (scoring) that takes into account criteria that cannot be directly monetized. This approach, although it does not completely eliminate the subjectivity involved in assigning scores and weights to various criteria (which ultimately leads to a single final index), makes use of Multicriteria Analysis to clarify the evaluator’s decisions. It also allows for the transparent comparison of preferences among stakeholders who may hold opposing views, thereby fostering constructive dialogue. The comparison between the alternatives was therefore developed by considering various aspects and, based on these, it was possible to determine which of the analyzed solutions was most suitable for the case. In conclusion, the design alternative with the highest score was considered to be the optimal from a qualitative perspective. According to the ranking considering environmental, functional/operational and economic criteria, the final choice was the direct intake near the coast, as shown in Figure 2.

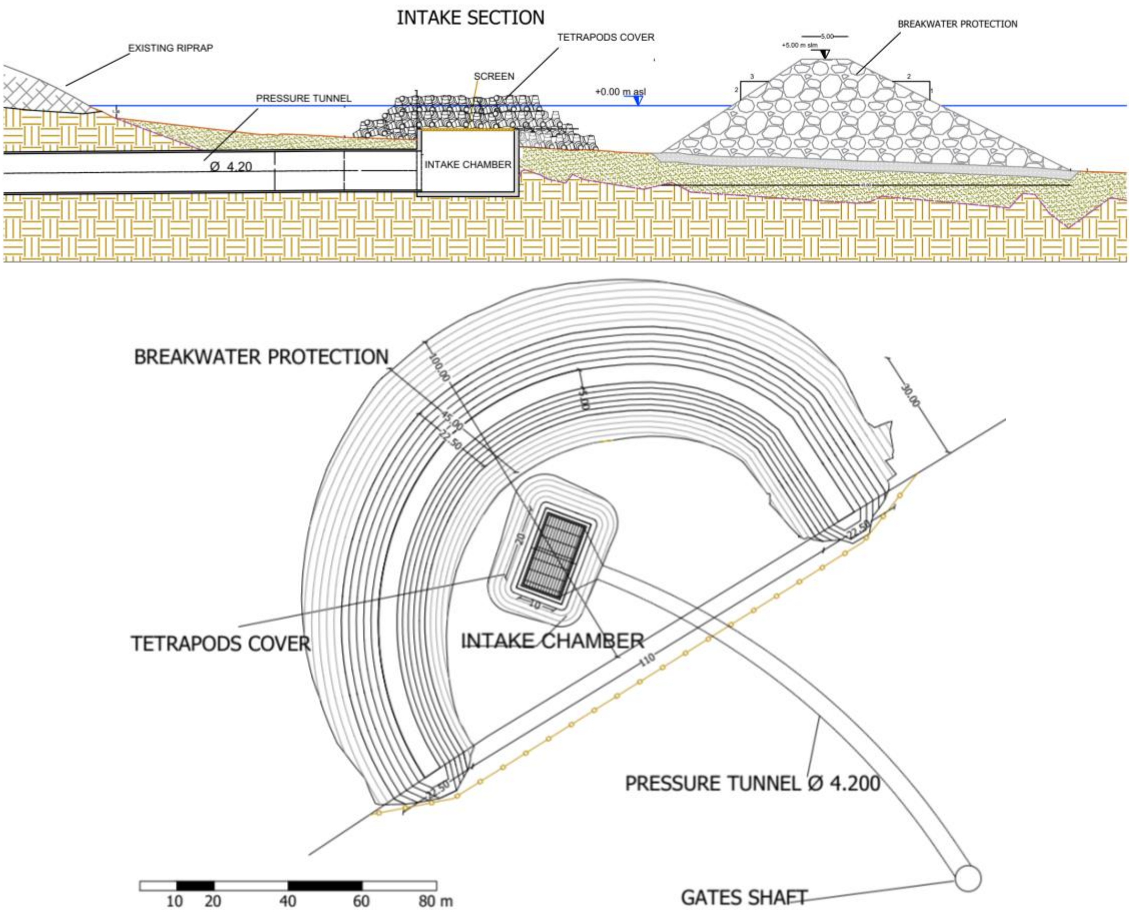

Figure 2 –Sea intake plan view and main section

2.3 Upper basin location and type of dam section

2.3.1 Constraints

In general, the choice for the location of the upper basin is driven by the following constraints:

- to maximize the head (morphology of the areas around the sea intake);
- to maximize the energy storage (maximize stored volume);
- to minimize the transport of materials for the construction of the reservoir embankment~~;~~
- to minimize the visual impact of the new structures.

2.3.2 Alternatives

The set of constraints mentioned above strongly reduced the suitable locations and the typological section (i.e., zonation) of the upper basin. As matter of fact, a single alternative was found to be suitable for the project.

2.3.3 Final selected solution

The location of the upper basin has been shown in Figure 1. It is located in a wide depression of the ground on a plateau at approximately 600 m a.s.l. (head maximization keeping the length of the waterways within reasonable values). The morphology of the site greatly minimize the visual impact (Figure 6) and the distance from the Transmission System Operator (TSO) substation, it maximize the stored volume (and therefore energy) while maintaining the economic feasibility of the project. Once verified the geotechnical characteristics and suitability of the huge amount of excavated material, coming from the excavation of waterways and underground powerhouse, to be used for the embankments construction, the resulting definition of the typical section can be seen in Figure 3.

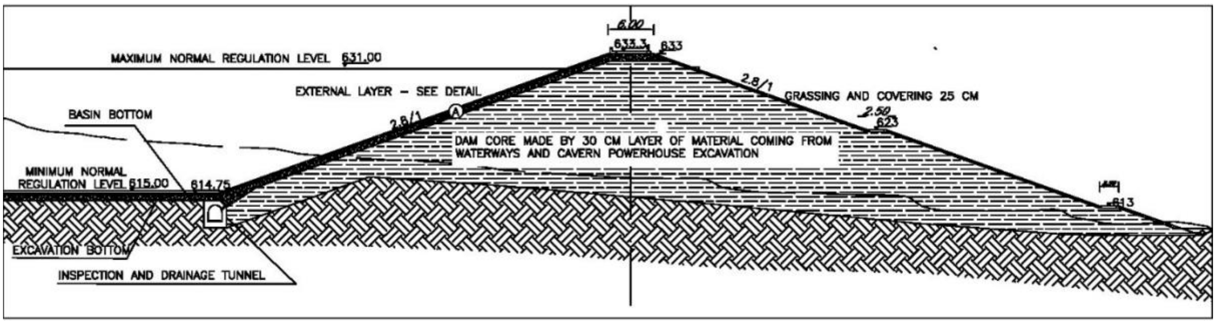

Figure 3 – Upper basin typical section

2.4 Upper basin waterproofing system

2.4.1 Constraints

The selection of the waterproofing system is primarily driven by the requirement to mitigate the risk of seawater infiltration, thereby preventing potential contamination of surrounding soil strata and underlying groundwater systems.

2.4.2 Alternatives

The considered alternatives were:

- Conventional waterproofing (concrete slab, asphaltic-concrete paving .)
- Double layer waterproofing system

2.4.3 Final selected solution

The reservoir will be waterproofed using a geocomposite membrane compliant with ICOLD Bulletin 135 (May 2010), laid over a 75 cm compacted drainage base. A 25 cm layer of gravel protection will be laid over the geocomposite layer.

Any leaks from the membrane, which are expected to be modest or non-existent, will be conveyed through the membrane base layer to the inspection and drainage tunnel. To prevent contamination of the groundwater within the dam body with salt water, the geomembrane base layer was confined with a second waterproofing layer made of High-Density PolyEthylene (HDPE). These leaks are conveyed to the inspection and drainage tunnel via pipes placed at 10-meter intervals, which pass through the concrete of the inspection and drainage tunnel and flow into an open drainage channel, then conveyed to the sea by a pipe installed in the busbar pit.

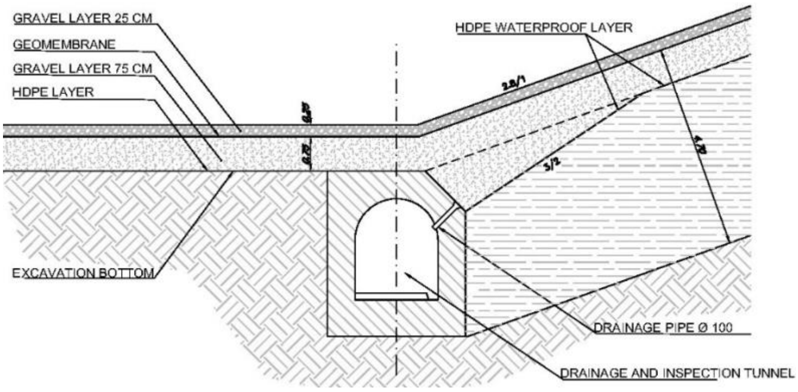

Figure 4 – Detail of the waterproofing system

2.5 Waterways and cavern powerhouse

2.5.1 Constraints

The type, position and dimensions of the upper basin heavily and prevailingly constrained all the other components of the plants, the waterways and the powerhouse as well. The main constraints on these two components were:

- Pumps must be 60 m below the average sea level (lower basin)
- Minimisation of the length of the cables connecting the ternary units to the substation
- Minimisation of the length of the waterways subject to high pressure

2.5.2 Alternatives

As for the position and type of the upper basin, the set of constraints were so strong that no reasonable alternative could be found at the solution briefly depicted below.

2.5.3 Final selected solution

The powerhouse has been designed underground, in a cavern located at -61.00 m above sea level, at a depth of approximately 700 m from ground level; the cavern is approximately 30 m high and has a floor plan of 118 x 22.5 m. The power plant houses two horizontal-axis ternary units (with Francis turbines). As you know, a ternary unit essentially consists of five components arranged on a single horizontal axis: a turbine, an electric machine that acts as both a generator and a motor, a pump, a coupling between the turbine and the motor-generator, and a torque converter between the pump and the motor-generator. This set of components enables hydraulic short-circuit operation, which allows for regulation of the power absorbed from the grid throughout the whole plant's pumping operation range (in theory from 0 to 100% of the nominal power of the pump) and also allows for minimal time intervals necessary for the transition between the generation and pumping phases. Specifically, shut-off systems are planned upstream and downstream of the hydraulic machines, allowing for maintenance without the need to empty the upstream basin and waterways. This shut-off function will be performed by four rotary valves, upstream of the machines, and four wheel gates, downstream of the machines, all hydraulically operated. Figure 5 shows the plan view and two sections of the power plant, corresponding to the turbine and the pump.

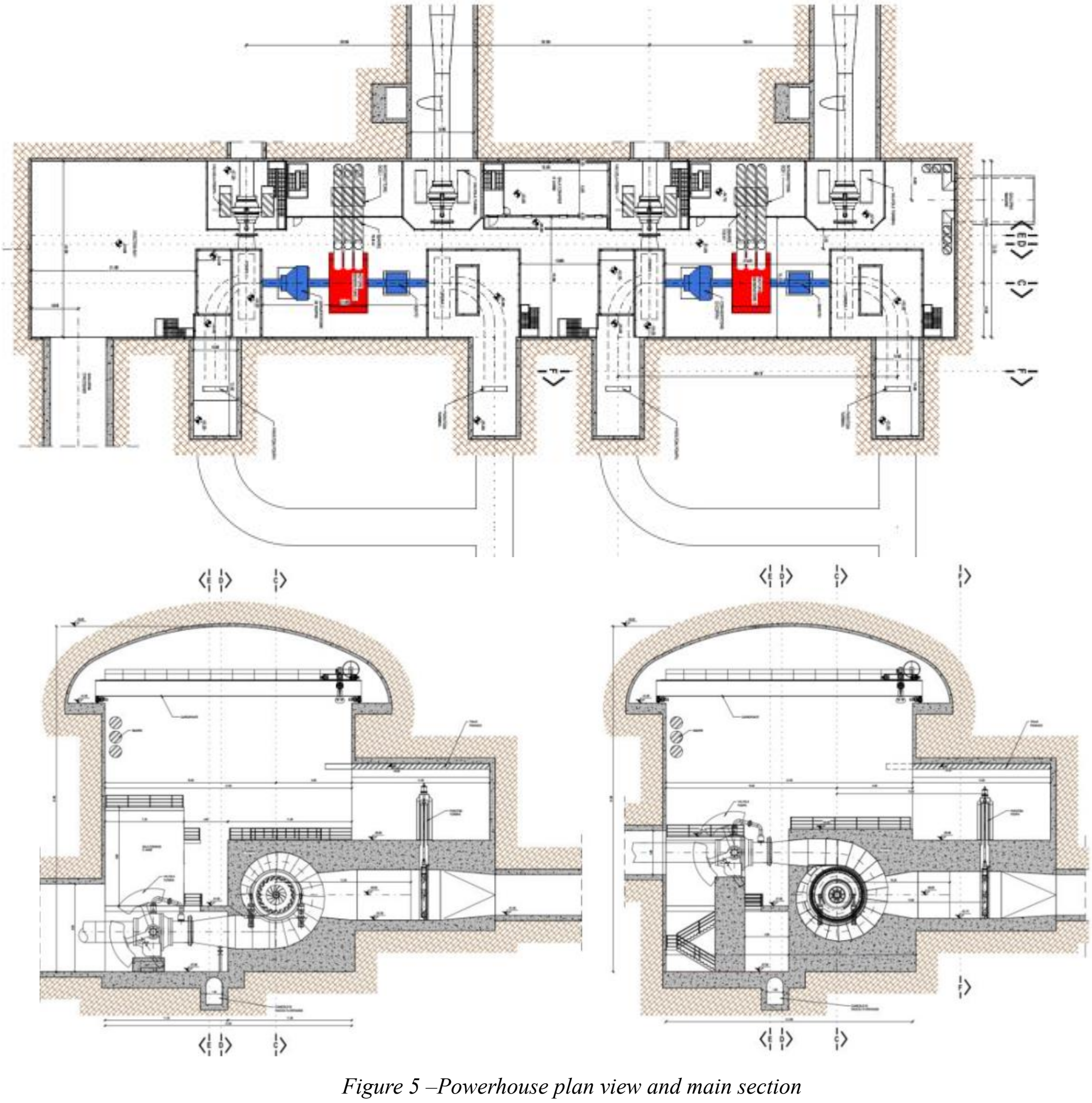

Figure 5 –Powerhouse plan view and main section

Once defined the location of the lower intake, of the upper basin and the powerhouse, the choice of the waterways layout was almost obligatory. From the intake structure (vertical shaft) at the upstream reservoir, passing through the underground powerhouse, to the downstream intake structure, an underground waterway with a circular cross-section and an internal diameter of 4.2 m is planned. This pipeline is approximately 5 km long and can be essentially divided in two main sections (from upstream to downstream):

1. A vertical section approximately 670 m long and a horizontal section 160 m long including two bifurcations, lined with metal pieces made of Super Duplex steel (Alloy 32750), which offers excellent resistance to stress corrosion cracking in chloride deposit environments and high resistance to general corrosion; they are typically used in marine applications. The pieces will be embedded with concrete. The penstock has been designed so that the metal pieces are self-resistant, capable of withstanding the overpressures expected during operation without requiring the -contribution of the surrounding concrete in the sections where it is grouted;
2. Downstream of the hydraulic machines, tunnels lined with reinforced concrete have been planned, which, after two series of connections, rejoin into a single DN 4,200 mm tunnel for a total length of approx. 4.1 km.

2.6 Grid connection

2.6.1 Constraints

As known, one of the remarkable costs of a PSP project can be referred to the grid connection, not only in terms of construction of a long HV transmission line, but also in terms of environmental impact (and authorization) of this infrastructure. That's why one of the main opportunity of the whole project has been the position of the existing TSO substation the new PSP had to be connected to. In fact, in the preliminary scouting phase, together with the morphological, geological and environmental aspects, the site was identified as suitable for a PSP development thanks to a quite large TSO substation close to the area.

2.6.2 Alternatives

As the point of connection to the grid was ~~constrained by the position of the~~ TSO substation, the main relevant alternatives were related to the position of the step-up transformers and of the relevant auxiliaries components:

A. Step-up transformers located in a cavern 700 m underground, close to the main ~~cavern~~ machine hall cavern;
B. Step-up transformers located outdoor close to the TSO substation.

2.6.3 Final selected solution

The solution adopted was alternative B. In fact, just to mention the main issues:

- both alternatives require a 700 m long busbar ~~duct~~ in a shaft
- HV cables have in general smaller heat losses and higher insulation costs
- MV cables have greater heat losses, smaller insulation and handling costs

Weighting pros and cons of both the solutions, keeping into account not only the investment costs but also the ease of O&M, alternative B seemed to be the best one. The MV busbars connecting the underground powerhouse to the step-up transformers start from the underground power plant and are housed inside a dedicated tunnel, 200 m long and with a slope of approximately 10%. At the end of the tunnel, the busbars curve upward and are installed inside a vertical shaft with an internal diameter of 7 m and a depth of approximately 650 m. At The top of this shaft is located the electrical substation. The busbar tunnel will be directly accessible from the underground power plant, as its bottom is at the same level as the power plant's main working level (-61 m above sea level). Inside the shaft, a pipe with a nominal diameter of approximately 350 mm will also be installed-, designed to convey water from the upstream basin drainage system and any water discharged from the upstream basin spillway downstream of the ternary units. This pipe will be equipped with appropriate diaphragm walls to dissipate the energy of the flow.

One of the challenging features of the plant has been the design of the cooling and ventilation system of the powerhouse and busbars.

3 Main environmental features

3.1 General environmental issues

In the Environmental Impact Assessment (EIA) some of the most usual environmental issues related with hydropower and pumped storage have been faced and solved, such as noise during construction and operation and impact of the underground components of the plant on the quantitative and qualitative status of groundwater resources. Furthermore, the authorities particularly focused on the visual impact of the project.

3.2 Visual impact

During the design phase, great attention was paid to the environmental impact of the works. Although much of the work is underground, the seawater intake structure and the nearby entrance to the power plant, the upstream basin with the nearby electrical substation, represent elements with an undeniable visual impact. The following actions were primarily adopted to mitigate this impact.

Upper basin and substation:

- the excavated soil and rock (derived from the excavations of the upstream basin) will be reused on-site, and specifically, part of this volume will be used to model the basin's embankment;
- the toe of the upper basin slopes will be planted to ensure optimal reconnection of the project with the surrounding context;
- to minimize the visual impact of the substation
  - the use of neutral colours or colours identified within the existing landscape context is planned;
  - a double row of native species of trees in staggered arrangement will be planted along the shorter sides of the substation yard, and a single row of native species of trees will be planted on the roadside and to the east of the substation, near the reservoir embankment. The single row of trees to the east of the substation will be flanked by a single row of multi-species shrubs.

Tunnel access portal and forecourt:

- The stone cladding materials and the colors of the structures will be selected from a specific palette derived from a color and material analysis of the surrounding landscape. Generally, the use of local materials is proposed (stone cladding in actual stone, or similar material that recalls the surrounding landscape in terms of morphological and visual characteristics).
- The external paving of the structure, as well as the widening and improvements to the road, will be made by materials that ensure good surface drainage and will use colors that reflect the surrounding landscape. The access gate and fences will be colored from the surrounding green palette, and their structure will ensure visual permeability and create continuity with the landscape behind them. Where possible, the surfaces of the access area to the gates shaft and the portal will be coated by grass, thus increasing and improving the microclimate and drainage of the surfaces.
- The use and selection of newly planted vegetation is expected to be dictated by the surrounding natural context to promote complete integration. Where possible, new trees and shrubs will be planted promptly, and valuable existing vegetation present in the construction areas and subject to removal will be replanted elsewhere, subject to appropriate stability and feasibility assessments. Bergamot (Citrus x bergamia) will be planted in order to ensure ecological continuity with the existing vegetation along the coast.

Sea intake

- The breakwater protection is the only structure relevant from a visual point of view (the other impacts are dealt with in par. 2.2). To integrate the breakwater into the landscape, we opted for the use of large natural boulders in neutral colors, aiming to maximize the integration of the structure with the existing coastline. Alternatively, painting some of the natural boulders of the breakwater in shades of green, derived from the surrounding landscape, was also considered as an option. This design option aims to reproduce the pattern of trees that grow on the natural slopes of the rocky outcrops of the mainland, making the breakwater a true landmark on the Favazzina coast.

Figure 6 - Rendering integration – Upper basin and substation

Figure 7 - Rendering integration – Tunnel access portal and forecourt

Figure 8 - Rendering integration – Sea intake

4 Remuneration

As you known, such a PSP project is highly capital intensive, some hundreds million euros of investment. Thus, it's necessary to have a reasonable degree of certainty about the remuneration of the services provided. The new Mechanism for the Procurement of Electricity Storage Capacity is not yet implemented yet for pumped storage in Italy and, first of all, also the mechanism structure is still under definition and the concrete operating rules are not defined. The system needs improvements in terms of reliability and security through the PSPs and their storage capacity, but energy operators need concrete mechanism to remunerate such capital intensive initiatives.

5 Replicability

Hydropower plants and PSPs are highly site-specific. The solutions taken are strongly constrained by local features. In terms of influence on the costs, the most critical specificities are usually related to geological and geotechnical issues. That's why in general it's hard to find easily replicable and on-the-shelf solutions. In this case, what we can highlight in terms of replicability, is the integrated approach to design, where, from the early stages, the interaction between the various disciplines, not only engineering, was constant, fully aware that the success of this type of initiative, while relying on appropriate technical solutions, also depends on social acceptance at large. Overall, while the fundamental concept and technology of pumped storage are highly replicable in a theoretical sense, the practical application is site-specific due to the unique combination of geological, environmental, and economic conditions at each potential location.

6 Conclusions

The previous chapters gave, even if shortly depicted, a quite comprehensive overview of the main features of a last-generation seawater pumped storage project planned by EDISON. Even though the challenging constraints and the well consolidated design approach, it appears that the technical feasibility of of the project is verified, although the remaining uncertainty of the regulatory framework.

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