Economic feasibility of underground pumped hydro storage systems in the Iberian Peninsula

Francisco Reis Pinto
francisco.reis.pinto@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

We are living through an extremely fast energy transition, where we are replacing power production from fossil fuels to renewable energy sources, such as wind and solar, especially in the Iberian Peninsula. However, this has its challenges, as for example, the need for energy storage that comes attached to it. With goals and pressure being implemented and forced by governmental and international organisations, a gold rush to the perfect energy storage solution has been happening. Battery storage has gained a lot of relevance in the past few years, due to its ease of deployment. However, battery storage cannot solve every problem related to battery storage, long duration energy storage solutions are needed. That is where solutions like underground pumped hydro storage gain an advantage. Therefore, in this paper an economic feasibility analysis will be done regarding the implementation of UPHS solutions in the Iberian Peninsula, running through various aspects, such as the market analysis, revenue assessment, a small technical design, a business case analysis and a SWOT analysis. Post analysis, it has been concluded that there is a huge potential for UPHS in the Iberian Peninsula, with opportunities for big revenues, but it requires large investments. It has been seen that there are more opportunities, than threats, but they cannot be ignored.
Keywords: Underground pumped hydropower storage, economic analysis, revenue streams, SWOT analysis

1. Introduction

With the development of renewable energy and its rapid implementation in many countries, some new problems and necessities have arisen, such as the unpredictable power production of renewable sources like solar and wind, its consequences to the grid, and the energy storage need derived from it. With the Iberian Peninsula being at a unique position for this energy transition, and due to it behaving like an energy island, it is in dire need of storage solutions, in order to continue implementing renewable energy sources and to stabilize its grid and solve possible constraints.

Pumped hydro storage then comes into play, as the obvious choice for long duration energy storage, but it is not without its problems. As any other hydropower project, it is highly dependent on terrain and water availability at surface level. Then a Swedish company called Mine Storage International (MSI) came up with a solution: installing pumped hydro storage underground in partially or fully flooded and decommissioned mines. With this transfer if the technology to underground, it aims to solve the constraints in implementation of this type of projects.

In this paper, the economic feasibility of such a solution in the Iberian Peninsula will be evaluated, considering several factors. It will go through an introduction to renewable energy and the methodology utilized in the analysis, followed by a market analysis, some calculations regarding potential revenues, a small technical design, a result analysis, a SWOT analysis and some conclusions and recommendations.

2. Renewable energy

Renewable energy has developing for the last 100 years, but the current boom in investment and demand have created a big spike in development and deployment of new installations. In the European Union (EU), several milestones have been achieved in the past 30 years, such as the solar and wind power production surpassing coal in 2019 and the establishment of a goal of 32% of renewable energy production by 2030 [1]. When it comes to this goal, not all countries in the EU have achieved, such as Spain, which was at a share of 21% as of 2021. On the other hand Portugal has surpassed it with a share of 34% as of 2021 [2].

On the main renewable energy sources is hydropower. hydropower has been established since the late 19th century and early 20th century. It is based on the concept of moving water from an upper reservoir to a lower reservoir, through a penstock to a powerhouse with turbines. The water movement, through the turbine is responsible to produce power in proportion to the flow, head (height difference between the surface of the upper reservoir and the surface of the lower reservoir) and gravity acceleration.

Pumped hydro storage (PHS) utilizes a similar concept to hydropower production, with a small difference. The process is reversible with the use of pumps. While using a pump, to transfer water from the lower reservoir, back to the upper reservoir, the installation consumes energy, to operate the pumps, and, therefore, works as a giant battery. Pumped hydro storage as a storage solution has been used for many years, being responsible for approximately 94% of the world's storage capacity, which corresponds to more than 9 thousand GWh of storage [3].

Underground pumped hydro storage (UPHS) utilizes the same concept as PHS, the only difference is that it is transferred underground, instead of having the necessity of looking for height differences at surface level, as seen in Figure 1.

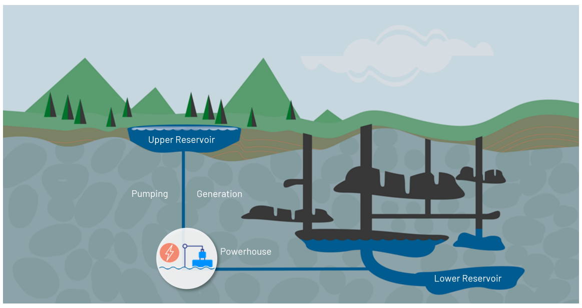

Figure 1: Underground pumped hydro storage schematic [4]

This ability of transferring the operation underground, where there usually are flooded mines and huge height differences, increases drastically the applicability of these projects and taking advantage of natural conditions to reduce costs. For example, a good solution, as seen in Figure 1 is to use a natural lake as the upper reservoir, and use flooded mining galleries as lower reservoir. With boreholes and shaft being part of normal mining explorations, they offer great opportunities for penstock installations and therefore potentially reducing the necessary excavations.

3. Methodology

To perform this economic analysis, a methodology needed to be developed with a structure as seen in Figure 2. Firstly, a market analysis is done, looking at the general characteristics of the target region, the Iberian Peninsula, including its topography, renewable energy production potential, availability of sites for UPHS (such as mining activity and potentially flooded mines) and grid conditions. Then, the market structure and governing bodies are researched to have a better understanding of how it works.

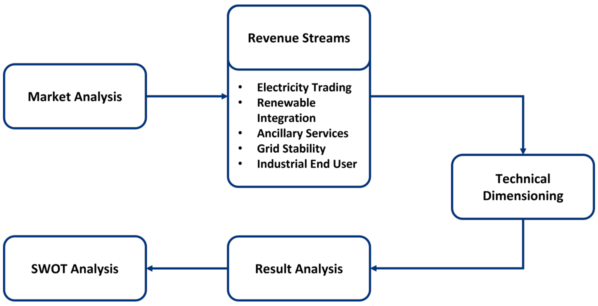

Figure 2: Methodology flowchart

Following this, an assessment on the potential revenues is done, where the electricity trading potential is calculated by verifying the average hourly difference in every day throughout a year. This is then corrected according to the assumed system efficiencies and the potential revenue for electricity trading is obtained.

Then an analysis on the potential revenue of renewable energy integration is done (more specifically, solar energy). To do this, several operational profiles are examined, with different storage times: 4, 6, 8 and 12 hours, with two different types of solar installation: ground mounted and floating and with two different production modes: production curve and production box. Having the operational profiles established, the economic value of implementing a storage solution is analysed by doing energy arbitrage, which is the shifting of production hours from the PV installations to hours where the electricity price is highest.

Other potential revenue streams are then analysed, such as ancillary services and grid stability services. Following this, two types of revenue streams for industrial end users will be calculated. One of the solutions will be the output stabilization of a PV installation, meaning that the production is stretched through the 24 hours of day, by reducing the output of power while the PV installation is producing energy and increasing it when it stops producing power, via the PHS installation. The other solution is establishing an off-take agreement solution, see ling the power at a contractually determined rate, lower than the market price, while buying it cheaper than the value established.

Post revenue streams calculations, a small technical design of an optimal storage time and type of renewable energy source is done, to understand how much capacity is needed in the UPHS to answer the capacity of each three exemplary PV installations established: 50 MW, 125 MW and 200MW.

Having obtained the technical design, three business cases are developed, considering the necessary assumptions, and creating optimal production cases. This business cases will be examined for key economic factors, such as the Net Present Value (NPV) and the Internal Rate of Return (IRR).

Finally, to help withdraw some conclusions, a SWOT analysis is done, looking at what are the project's strengths, weaknesses, opportunities, and threats. This information is used to help develop the conclusions and the author's recommendations for future work.

4. Market analysis

To do the market analysis, it was important to understand some of the general characteristics, such as its topography, energy resources, mining resources and its grid condition. The Iberian Peninsula has a unique topography, being very mountainous around its edges, with two large flat plains in the middle of Spain, separated by the Sistema Central, a mountain chain. Important to highlight are the mountains in the northern part of the Peninsula, where there is a lot of water presence and height variations.

Regarding its energy resources, the Iberian Peninsula has a big capacity to produce solar energy, being in the southern tip of Europe, it has a lot of solar exposure, which increases the irradiation that it is subject to. It also has a good position to produce renewable energy from wind power, due to its big coastal area, it has potential to produce offshore wind power.

When it comes to mining resources, the Iberian Peninsula has had mining explorations for millennia. It currently has various explorations throughout the Peninsula, with a focus on the northern part of it, in Asturias, Cantabria, Coruña and Aragon. It also has a large potential in flooded mines, according to the research done by the EU funded project UNEXMiN [5], as seen in Figure 3, represented by the red dots.

Finally, regarding the grid condition, according to ENTSO-E, the grid development in the Iberian Peninsula is good, with a high density in the northern region, matching up with the high industrial and mining activity that occurs there. It has some less dense regions in the south [6]. Regarding its interconnections, Portugal has a very good interconnection rate, whereas Spain doesn't. The EU has established a goal of 15% of interconnection rate, which has been achieved by Portugal, with its several interconnections to Spain, but not by Spain, with a current rate of approximately 6%, making the Iberian Peninsula a sort of energy island [7].

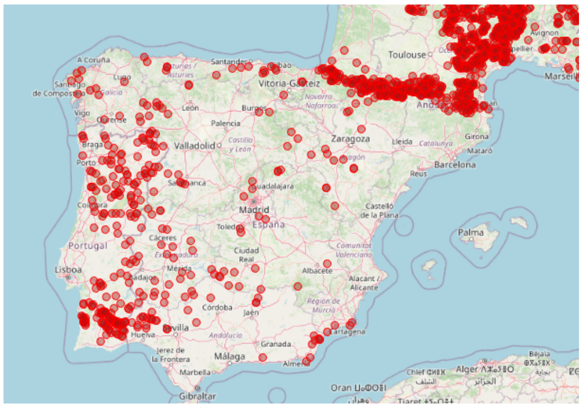

Figure 3: Potentially flooded mines in the Iberian Peninsula [5]

When it comes to the market structure, it has a very peculiar one. Spain and Portugal are combined into one electricity market called the Mercado Ibérico de Electricidade (MIBEL). Each country produces its own energy and operates it within its borders while needed. Only after passing through the Transmission System Operator (TSO) and Distribution System Operator (DSO) it goes into MIBEL. If, by then, there is excess energy, only then it goes into the European Internal Energy Market, as it can be seen in Figure 4.

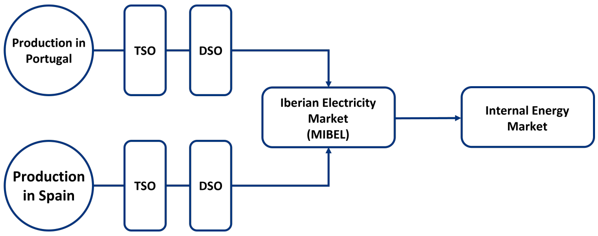

Figure 4: MIBEL market structure

As regulatory bodies, to ensure a fair management of the market, there are two organizations OMIP and OMIE, with OMIP being the Portuguese counterpart and OMIE being the Spanish counterpart. OMIP oversees the Futures market, whereas OMIE is responsible of regulating the Intraday market and the Day-ahead market.

5. Revenue assessment

To perform the necessary calculations for each revenue stream, some assumptions regarding efficiencies were made, seen in Table 1. Where turbining refers to act of running water through the turbines, pumping is the reverse operation and total system is the round-trip efficiency.

Table 1: Process efficiencies

Process	Efficiency
Turbining	91%
Pumping	87%
Total System	79%

5.1. Electricity trading

The electricity trading potential revenue was calculated with data extracted from *OMIEData* [8], regarding one year of spot prices in MIBEL. With this data, the difference between the maximum and minimum daily prices was calculated and the average of the result was obtained. In addition, the average spot price was also calculated to create an idea of the spot prices in the Iberian Peninsula. The results were as seen in Table 2.

Table 2: Spot price characteristics and potential revenues from electricity trading

Spot Price	Max	300.00	€/MWh
	Min	0.00	€/MWh
	Average	115.48	€/MWh
Potential Revenue	Max	212.03	€/MWh
	Min	15.36	€/MWh
	Average	81.98	€/MWh

5.2. Renewable energy integration

To calculate the potential revenues from renewable integration, data was drawn from *Solar Atlas* [9], regarding the operational output of a 1 MW ground mounted photovoltaic installation with 30 degrees of inclination and a 1 MW floating photovoltaic installation with 10 degrees of inclination, both located near Zaragoza, Spain.

Several operational profiles were calculated, taking into account the previously mentioned efficiencies, with 3 different cases for each storage time, with an exception for the 12 hour storage, which only had one case. In addition, all cases were tested with both a production curve and a production box, production curve meaning that they were tested with production factors that simulated a curve, to mimic a turbine that start with low production, achieves a peak in the middle of its operation and then reduces power production again. In regard of the turbine box, the simulating factors were constant, mimicking a turbine that always produces the same constant rate of power, because it can start producing power at a constant rate almost immediately (in seconds or minutes, which is irrelevant in power production because it occurs in a hourly rate).

After the operational profiles were obtained, the effective production output of the solar farm or the PHS system (they never occur at the same time) were multiplied by the average spot price for each hour in each month, obtaining a revenue. Then to do a comparison, the original profit from the PV installations was calculated by multiplying its production with the average spot price and its result was compared with the profit result when combined with the PHS, where the added value was obtained as seen in Equation (1):

$$AV = P_T - P_{PV} \tag{1}$$

where AV represents the added value, P_T is the total profit of the combined production of the PV installation and the PHS system and P_{PV} is the original profit of the solar installation, without storage and

$$PI = \frac{AV}{P_T} * 100 \tag{2}$$

where the profit increase (PI) is obtained by dividing the added value by the total profit and multiplied by 100, to obtain a percentage.

The results that were obtained were separated according to the type of the PV installation. In Figure 5, the results for the ground mounted installation can be seen. It can be observed that the 12 hours storage time results in negative profit increase, due to the peak energy prices coinciding with the optimal time to run the pumps, losing profit by not outputting it to the grid. It is also important to mention that the 6 hours storage time results were the best, with profit increases of 7.3% in the worst case and 9.4% in the best-case scenario.

Regarding the floating PV installation, the results were consistently worse, probably due to the reduced inclination considered (10 degrees versus the 30 degrees of ground mounted). Alike with the ground mounted installation, the only negative result came from the 12 hours storage time, with the inability of keeping up with the price spikes remaining. The overall best results came from the 6 hours storage time, with the profit increases ranging between 7.0% and 8.9%.

It is also important to mention the difference in profit increases between a turbine curve and a turbine box in both types of installations. This is due to the turbine production box not being able to reach the peaks of electricity prices like the turbine production curve can. Its constant output hinders its ability to reach these higher prices.

5.3. Ancillary services and grid stability

On the revenue assessment of ancillary services, a conclusion was achieved. Despite existing an ancillary services market in the Iberian Peninsula, its structure is still a bit premature, with very variable and unpredictable remuneration systems. Therefore, it was purposely left out in the calculations.

Regarding the grid stability type of revenue stream, talks have been happening in the past years of the implementation of a capacity market in Spain, but despite the approval of a regulation system, it hasn't been put into place, and there is no official information of when it will happen [10]. In consequence, it was also left out of the calculations.

5.4. Industrial end user

Regarding the industrial end user, two options were attempted. The first option endeavoured was

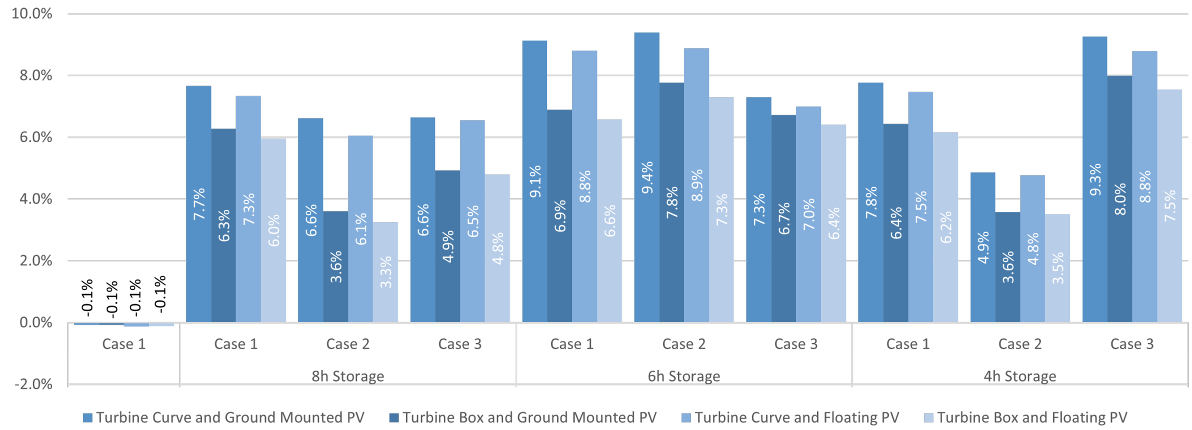

Figure 5: Added value of a PHS solution combined with a ground mounted PV installation and a floating PV installation with different turbine operation settings

the implementation of a constant output of the energy produced by a PV installation. This was done by diving the total production of the solar farm through the 24 hours of the day, by pumping with the PHS system, while it was producing more than hourly average and utilising the turbines to produce power when the solar farm was producing less than the hourly average.

Similarly to what was done in the renewable integration, the variation in profits was calculated and, as seen in table 3, the results were very positive. There was no need of implementing a production curve or box since the output was constant. With a profit increase of 7.5% for the ground mounted installation and 7.7% for the floating installation, these results are like what was achieved with the 8 hours storage time in the renewable energy integration.

Table 3: Industrial use profits comparison with different PV installations

PV type	Profit Increase
Ground mounted	7.5%
Floating	7.7%

When it comes to the off-take agreement, it was established that, to simulate a contractual agreement, the value that it should be set to was half of the average spot price, round up to the nearest ten. This would allow the PHS installation to pump water while the electricity prices were below 60€/MWh and turbine them when the off taker needed so.

6. Technical design

To obtain the technical design of the facility, a proportion was used. In this case, to simplify, the best case scenario achieved in the renewable integration section (Section 5.2, which was the 6 hours storage solution for the 1 MW ground mounted PV installation with a production curve was used. By obtaining the absolute maximum of its turbine energy production and pump energy consumption, the proportion was established to three different fictional PV farms, with capacities of 50 MW, 125 MW and 200 MW and calculated as seen in Equation (3):

$$P_{PHS} = \frac{P_{PV_{farm}} * P_{PHS_{1MWmax}}}{P_{PV_{1MW}}} \quad (3)$$

where the capacity of the PHS system (P_{PHS})is calculated by the multiplication of the capacity of the photovoltaic farm ($P_{PV_{farm}}$) and the maximum needed capacity in the PHS when pairing with a 1 MW solar installation ($P_{PHS_{1MWmax}}$) and divided by the capacity of the initial PV installation ($P_{PV_{1MW}}$), which was 1 MW.

The results derived from this calculation, per each case, were as follows in Table 4:

Table 4: PHS capacity calculation results

PV farm		PV farm I	PV farm II	PV farm III
PV size		50 MW	125 MW	200 MW
PHS size	Case 1	33 MW	82 MW	131 MW
	Case 2	38 MW	94 MW	150 MW
	Case 3	38 MW	94 MW	150 MW

With these results, it could be seen that despite the different operational profiles, both case 2 and case 3 needed the same size of storage installation, due to achieving the same energy peak. Case 1, on the other hand, needed a smaller installation.

7. Result analysis

Following the results of both Section 6 and Section 5, three different cases were developed to better understand the economic feasibility of each one. But firstly, some assumptions regarding the remuneration of each case were needed. As previously mentioned, the electricity trading revenue was resultant of the average difference between daily maximum and minimum spot prices. The remuneration of the off-take agreement was assumed as 50% of the average some price and round up to the nearest ten, which was 60€/MWh. The revenues from ancillary services were considered as zero, due to their complexity and unpredictability. Finally, the revenues from renewable energy integration were considered as half of the profit increase that it could benefit in the optimal case, which was the 6 hours storage with a ground mounted PV installation and with a turbine production curve.

As costs, DEVEX of 2 million euros, CAPEX of 1.5 million euros per MW of capacity and OPEX of 3% of the CAPEX were considered. Finally, the business cases were calculated for the period of 20 years of operation, plus one year for DEVEX and one year for CAPEX and the approximate results for the main economic indicators, IRR and NPV were as it can be seen in Table 5:

Table 5: Economic indicators' results

PV farm		PV farm I	PV farm II	PV farm III
Case 1	NPV	10.8 M€	27.8 M€	44.9 M€
	IRR	6%	7%	7%
Case 2	NPV	12.6 M€	32.2 M€	51.8 M€
	IRR	6%	7%	7%
Case 3	NPV	12.0 M€	30.8 M€	49.6 M€
	IRR	6%	6%	7%

It can be observed that despite case 2 and case 3 having a similar size, due to their different operational profiles and consequent different profit increase of renewable energy integration, their economic indicators are quite different. In case 2, there is almost an increase in NPV of 2 million euros at the end of 20 years, but the most outstanding difference is the difference in IRR between case 2 and 3 for the sample PV farm II, with a decrease in 1%, which can be very significant.

8. SWOT analysis

After all the calculations were made, a SWOT analysis was done, as seen in Figure 6. The project strengths were significant, with pumped hydro storage being utilised for more than 50 years, it is considered a mature technology, with not many risks attached to it. Its high efficiency is a consequence of being such a developed technology, with turbines being able to achieve 90% of efficiency and pumps going up to 80%, even when taking a conservative approach as it was done in this dissertation, the round-trip efficiency is approximately 80%. These two strengths, combined with the growing need for long duration energy storage solutions, makes this type of project ideal to support large scale consumers and producers, especially when compared with the trendier battery storage.

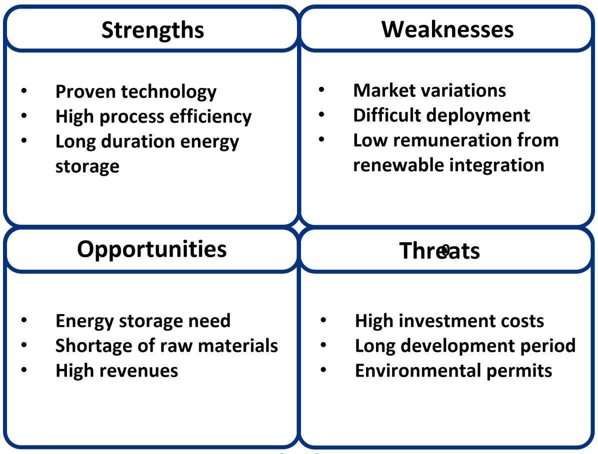

Figure 6: SWOT analysis

Nevertheless, every project has its weaknesses, and for underground pumped hydro storage are its high dependence on electricity market variations, being subject to price fluctuations, which can make any type of prediction unreliable. It also has a difficult deployment, when compared to other energy storage solutions, a UPHS project can take around 5 years from qualification to operation, if not more, which can be a major hindrance to its development. Finally, as proved in the previous chapters, it cannot work solely based on remuneration from renewable energy integration, due to low margins. It needs other revenue streams to strengthen its business case and make it more economically viable.

The major opportunities regarding UPHS in the Iberian Peninsula are the growing energy storage need, not necessarily long duration energy storage, but all types. With this need and its flexibility, a UPHS can answer the need in matters of minutes, hours or even months, providing a flexible storage that not many others can. Due to the shortage of raw materials that we are living through, other types of storage, such as battery storage, are having troubles answering the rising demand. PHS, being a much simpler technology and requiring more common materials, has an edge on this. Finally, as proven in the previous chapters, it can provide very high revenues, when correctly configured with the market operation.

At last, the potential project killers and things that can be threats are its high investment costs, long development period and difficulty in acquiring environmental permits. Despite the high revenues that it can provide, UPHS also requires very high investments, which can be very hard to achieve without proper justification. Its long development period, usually taking almost three years in qualification and development can cause UPHS solutions to be put aside in favour of more streamlined solutions.

Finally, the most serious threat, the concerns regarding the environment. As in any mining environment, there can be very hazardous materials that by having any artificial interaction can cause major pollution problems, such as acid drainage in sulfuric mines and methane release in coal mines. Because of that, every project needs to be carefully examined before being put action, as well as it can difficult the acquisition of the needed environmental permits, without the proper studies to support it.

9. Conclusions and recommendations

9.1. Conclusions

As seen in this paper, there is economic feasibility in implementing underground pumped storage solutions in the Iberian Peninsula. It has a market with potential, with the adequate topography, especially in the northern part of the peninsula, with a huge potential for solar and wind power production, various flooded mines opportunities and a strong grid, with good interconnections inside the Peninsula for implementation of this type of projects.

It has also been concluded that there is very high potential in revenues, especially in electricity trading, which has very high revenues, but it is subject to high risks, renewable energy integration, which can have a stable and strong stream of income in 6 and 4-hours storage solutions and industrial end users, when under an off-take agreement. On the other hand, it has been seen that there isn't an adequate ancillary services market, still very premature, and there is no capacity reserve market at all, despite rumours.

On the technical design, t has been shown that the UPHS needed a much lower capacity than the PV installation that they might be coupled to, offering a good opportunity fr profit increase when combined. On the side of the result analysis, it was possible to see that the operational profile is key, because despite two cases having UPHS installations of the same size, they had very different revenues, and different IRR's.

Regarding the SWOT analysis, there are a lot of strengths to these projects and, when combined with the opportunities, they become very strong. However, the threats are there, such as the environmental concerns, and those have the power to put a project to a halt if not dealt with appropriately.

Therefore, the Iberian Peninsula is a good opportunity for companies like MSI and their UPHS solutions, but some precautions should be taken in order to ensure stable and safe revenue streams, rather than high risk and high revenue, and to ensure that the potential project killers are controlled and contained.

9.2. Recommendations for future work

Regarding future work, the author recommends that better price forecast options are used, in other to increase the reliability of the revenue calculations. The paper could be also improved by examining some site-specific locations and building the business cases around those constraints, such as available water volume and head.

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