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EXECUTIVE SUMMARY OF THE THESIS

Underwater CAES for off-shore wind farms: system integration and operating strategy optimization based on techno-economic analysis

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

The increase in the energy demand worldwide accompanied by the need to reduce greenhouse gas emissions, has led in the last decades to an increasing use of renewable energy sources. Due to their non-programable nature, especially of solar and wind sources, a problem in the management of their energy production occurs, leading to new challenges. In this scenario, the technologies able to store energy can help to improve the electric grid management. Different solutions for large-scale storage systems have been proposed in the last years, such as the Pumped Storage Hydropower system, that is already well established, chemical storages (batteries or gas storages), and the compressed air energy storage system (CAES). This last option was proposed for the first time in 1949 by S. Lavale, but only two plants have been built: in Huntorf, Germany, in 1978 with a nominal power of 290 MW, and in McIntosh, Alabama, in 1991 with a nominal power of 110 MW [1]. These plants use caverns to store air, thus with a constant storage volume and a change in air pressure during the plant operation. Furthermore, they are diabatic systems that need to burn fuel to heat up the air flow before expansion through the turbine. These problems limit the achievable round-trip efficiency (RTE), and for this reason other plant solutions were proposed. The underwater adiabatic alternative (UW-CAES) is the system that better solves these problems, thanks to the introduction of a thermal storage system (TES) and tanks placed on the seabed to store air at a constant pressure. An example of layout is shown in Figure 1.1. A compressor increases the air pressure from the ambient to the underwater one, and consequently the air temperature rises. Then, the air flow is cooled passing through three heat exchangers (HX) in series, using three different thermal fluids (TF): solar salt, thermal oil, and water. A TES stores the thermal energy of the hot TFs, providing it to the process at a later time to heat up the air flow avoiding fuel consumption. The air at low temperature is then stored in the underwater air tanks, ready to flow across the plant in opposite direction being heated by the TES. Subsequent expansion through a turbine connected to an electric generator, allows to produce electric energy. Different plant layouts can be considered: turbomachines and TES on land connected with the air tanks by means of a pipeline, or an off-shore platform to locate them directly in the air storage site. The main difference is the need for a pipeline in the first case, that can have a length of several kilometers to reach the required seabed depth, introducing non negligible pressure losses. Regarding the air storage system, pressure is kept constant by the hydrostatic pressure given by the seawater column above the tanks, that can be made by rigid structure of concreate with an open at the bottom, or flexible fabric structure.

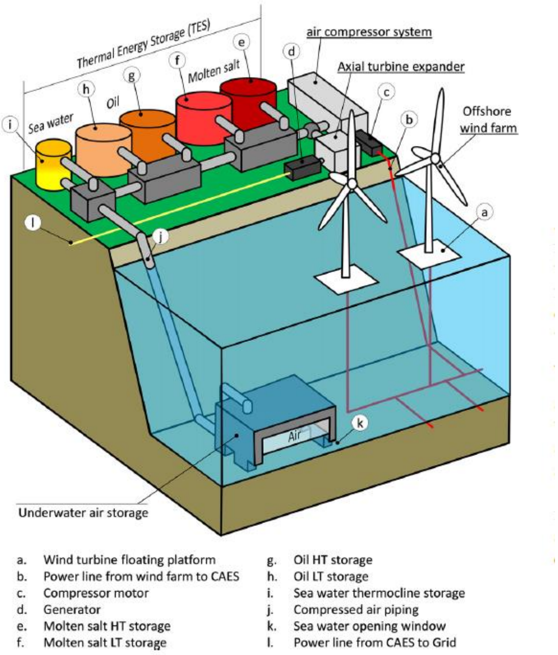

Figure 1.1: UW-CAES configuration coupled with an off-shore wind farm.

In this thesis an UW-CAES system coupled with an off-shore wind farm (WF) is analysed, considering turbomachines and TES on land and a pipeline to bring air to the underwater tanks. Both rigid caissons and energy bags are considered, the former with a volume of 5000 m³ and the latter of 36000 m³. Basing on proposed WF in the Italian seas, the design and annual operation of an UW-CAES plant are assessed, completing the analysis with its economic feasibility evaluation. To do that, a specifically built MatLab model is used to take into account how different components of the plant interact. Furthermore, in all cases in which thermodynamic air properties are necessary, they are calculated by means of CoolProp library.

2. Methodology

2.1. Plant Design

The first step to evaluate an UW-CAES system is to proceed in the design of the plant, based on the off-shore WF specifics: nominal power P_{WF}, distance from the coast and sea depth. They are crucial constrains, since they impose pressure at which air is stored and length of the pipeline that mostly affects pressure drops along the plant. The P_{WF} instead, is used to dimension in a proper way the compressor, since its activation depends by the wind farm power output. The dimensioning of the different components of the plant in design conditions, is carried out considering that the plant can work in two different modes: Cooling to Storage (CtS), that represents the charging phase, or Heating from Storage (HfS), that indicates the discharging phase.

During CtS phase, a compression train, which configuration is taken from a previous work [2], rises air pressure above the underwater one to overcome all the pressure drops. It consist of three compressors in series, one axial and two radial, with an intercooler (IC) between the first two. The introduction of the IC is necessary to control the compressor outlet temperature (COT) and at the same time reduce the work absorbed during its operation. In particular, the COT is kept to 625°C to optimise the following heat exchange, since a $\Delta T_{pp,HX}$ of 25°C is assumed and the maximum temperature the solar salt can face is 600°C, above which it become unstable. Given WF location and established the compressor nominal power P_c, a system of equations to calculate the air mass flow rate $\dot{m}_{air}$ is solved, considering pressure drop across the pipeline Δp_{pipe} and across the HXs. Also, the IC outlet temperature (IOT) is kept fixed in design condition, equal to 24°C. In fact, a counterflow HX using sea water at 14°C is assumed, with a $\Delta T_{pp,IC}$ of 10°C. Solving the IC energy balance, it is possible to evaluate the sea water mass flow rate needed to cool down the air, other than thermal power exchanged and the UA parameter, in which A [m²] is the heat exchange surface and U [W/m²·K] the global heat transfer coefficient. But it must be considered that to reinject the water into the sea, its temperature cannot be higher than 35°C as imposed by the Italian legislation. The UA product is fundamental to study the off design of IC since the surface is fixed once dimensioned.

Then, considering the thermodynamic properties of TFs and range of temperature in which they can varies [2], it is possible to solve for each HX a thermal balance, to find out the TFs mass flow rate, the exchanged thermal powers and the UA parameters, carrying out the cooling process across the TES. To optimize this heat exchange process, a constant thermal capacity between hot and cold fluid is taken in CtS phase. The TFs are heated up and stored in the TES, and the air, at the exit of the last HX that use sea water as TF, flows through the pipeline into the air tanks.

At this point the HfS process can be evaluated in design conditions. The turbine dimension factor TDF is introduced to better perform the analysis of the plant, as the ratio between $\dot{m}_{air}$ of compressor and turbine and is assumed equal to 1 to optimize the heating process, leading the HXs working with the same air mass flow as during CtS phase.

Air is assumed to be in thermal equilibrium at 5°C with the surrounding seawater when it is stored. Thus, solving the energy balance for the HXs, the mass of TFs needed to heat up the air and the turbine inlet temperature (TIT) are carried out. The turbine power output P_t can be evaluated at this point, knowing its inlet temperature and pressure.

The last components that need to be sized are pipeline and air storage system, instead the number of tanks to store TF is evaluated basing on the annual plant operation. The necessary pipeline wall thickness must be evaluated to face difference between operating and external hydrostatic pressure, that is maximum at the pipe inlet during CtS phase. Then, to balance the buoyancy force and improve stability, a concreate coating is assumed to add weight to the steel pipeline.

Regarding the air storage instead, the number of required tanks is determined by defining the continuous operating hours $h_{max,T}$ to be guaranteed to the turbine in design condition. Thus, knowing the $\dot{m}_{air}$, $h_{max,T}$ and air density, the necessary volume of air, and thus number of tanks, is calculated.

2.2. Off-Design

During plant design, the two phases CtS and HfS could be analysed independently, but now operation in one or the other mode, or even plant shutdown, is determined hour by hour on the basis of wind availability, electric energy price, and amount of stored air and thermal energy.

The following Figure 2.1 shows how the different constrains influence the plant operation and how the written model on MatLab works.

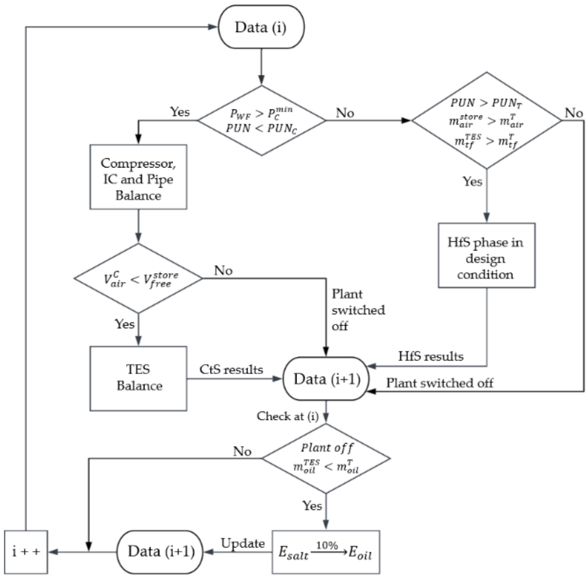

Figure 2.1: Flow chart of plant operation in off design conditions.

For each hour of a year, if the power output of the WF is high enough and the electricity price PUN is cheap enough, the compressor can run and a system of equations considering compressor, IC and pressure drops across the pipeline is carried out to calculate the $\dot{m}_{air}$ and thus the amount of air elaborated by the compressor that hour. This check is necessary to ensure that air tanks have enough space to store it and thus run the plant in CtS mode. Otherwise, if at least one of the first two constrains is not satisfied, the model evaluates if the turbine can run, checking if the PUN is high enough and if enough air and TFs are stored. In that case the plant can work in HfS mode, and the same results of design are used since the turbine always runs in design conditions to guarantee best performance both during heating process and expansion.

When both compressor and turbine cannot operate, the plant is switched off. In all these cases, the data are updated with the results given by the operation in the hour under consideration, to be

used for the plant evaluation during the next hour. But since the consumption of thermal oil is higher during the heating process than other TFs, can happen that turbine cannot work due to lack of hot stored oil. To limit this problem another HX is introduced to transfer heat from solar salt to thermal oil. Computing this process for all the 8760 hours during a year, is possible to simulate how the plant works, evaluating performance parameters such as equivalent hours h_{eq} of compressor and turbine, number of start-ups, energy stored and produced, and plant RTE. It is possible to monitor the air tanks filling status calculating the cumulative mass of air. And with the cumulative mass of TFs is possible to define the maximum mass necessary for each fluid and thus the number of thermal tanks, considering vessels with an inner diameter and height of 20 meters.
In particular, what mainly differ during off design is the compression phase, which results are obtained solving a system of 30 equations, that basing on the design results, allows to solve the compressor-IC-pipeline balance. In fact, during the off design the IC outlet temperature IOT is an unknown, thus also its energy balance has to be solved together with the other equations. The compressor in off design can work following a certain efficiency curve taken from [2] as an example of a possible real case.

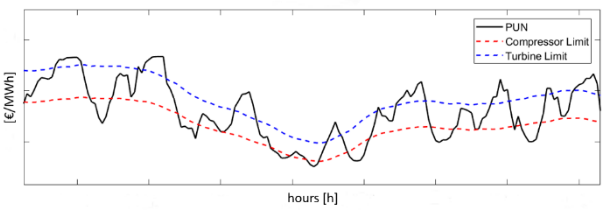

Figure 2.2: Example of used logic for activation of turbomachines with a margin of ±10% on the moving mean of PUN.

Regarding the electricity price PUN, firstly a logic based on the mean value during the year was considered, using a certain range around it as thresholds for compressor and turbine activation. Then, to improve plant performance trying to increase h_{eq}, a logic based on the moving average of PUN was investigated to better follow its trend, as shown in Figure 2.2.

2.3. Economic model

To make possible an economic evaluation of the studied UW-CAES plants, the Levelized Cost of Storage LCOS is calculated over the plant lifetime considering a Weighted Average Cost of Capital (WACC) of 7%. Firstly, capital and operating expenditures (CAPEX and OPEX) are carried out starting from available data in literature [3], and the investment costs are actualized by means of the Chemical Engineering Plant Cost Index (CEPCI [4]), that take into consideration costs changes of plant equipment by years. Then, knowing the energy produced by the turbine and yearly costs to run the compressor, the LCOS can be assessed. In particular, the hourly PUN is assumed as cost for compression, allowing to only evaluate the convenience of the UW-CAES system, even if coupled with an off-shore WF. Other economic parameters are considered such as the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Pay-Back Time (PBT).

3. Results

3.1. Case Study

The MatLab model was applied to the proposed off-shore WF of San Pietro in Sardinia, located at 30 km from the coast with a sea depth around 500 m and a nominal power of 200 MW. Using a compressor with a nominal power P_c of 50 MW, the design of the plant and its operation during a year has been analysed starting from power output forecast of the WF. Three different PUN have been chosen: 2019, 2020 and 2022. The first represents the electricity price on the Italian wholesale market before Covid pandemic, 2020 during the pandemic with small variation of prices, and the last one is affected by the war in Europe, with prices varying over a wider range and with greater fluctuation.
From the plant design is evident the impact of the pipeline, that with an inner diameter of 0.5 m led to a pressure drop higher than 8 bar, as well as representing an important part of the investment costs, with a CAPEX of 350 M€. Regarding the operation during the year, the difference between the two logics based on moving mean PUN and annual mean PUN is shown in Figure 3.1, referring to San Pietro plant operation in 2019. The blue lines represent activation of compressor for positive power values, and activation of turbine for negative values. It is clear that the moving mean logic allows to sensibly increase the plant h_{eq}.

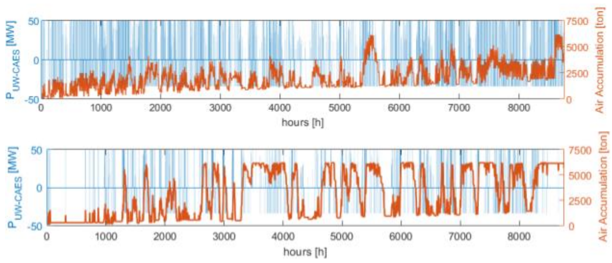

Figure 3.1: San Pietro plant operation in 2019, using the moving mean PUN logic on top, and the annual mean PUN logic on bottom.

Then the introduction of the solar-oil HX can be discussed, because as shown the Figure 3.2, it allows to transfer thermal energy from solar salt to thermal oil when the latter present a lack of energy availability, but at the same time it leads to a total consumption of solar salt. Hence, the logic based on the transfer of 10% of salt energy to the oil brings to the opposite problem.

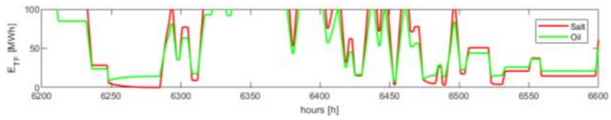

Figure 3.2: Detail of energy storage trend to highlight salt-oil HX operation.

The economic analysis returns CAPEX of 1129.2 and 567.3 M€ using rigid caissons and energy bags respectively. Considering this second option that is cheaper, the main results of the plant performance are reported in Table 3.1. The impact given by the PUN differences for the considered years is evident both in the h_{eq} and LCOS of the plant, but the RTE is not much affected, with values around 67.66%.

Parameter	2019	2020	2022
$\boldsymbol{h_{eq,c}}$ **[h]**	1768	1972	1498
$\boldsymbol{h_{eq,t}}$ **[h]**	1756	1961	1491
$\boldsymbol{LCOS_{EB}}$ **[€/MWh]**	1168.3	1039	1645

Table 3.1: Main results of San Pietro plant in 2019 using energy bags.

3.2. Other Plants

Other simulations has been done considering other two plants, Trapani and Catanzaro, that differ from the case study for sea depth and especially distance from the coast: the former at 53 km and the latter at 15 km. The P_c is 100 MW and 83 MW respectively, thus higher air mass flow rate are obtained. As already told the pipeline is one of the major costs of the plant in San Pietro and the Δp_{pipe} that it entails affect the RTE. In fact, with the same pipe diameter as for San Pietro, a RTE of ~68.4% is achieved for Catanzaro plant, thanks to smaller distance from the coast and deeper sea even if with higher $\dot{m}_{air}$. For the Trapani plant instead, a RTE ~69.5% is obtained using a pipe diameter of 0.8 m, that is necessary to manage the higher $\dot{m}_{air}$ and the much higher pipeline length. Considering PUN in 2020 that leads to lower LCOS, the Catanzaro plant presents a LCOS of 520.9 €/MWh and Trapani of 1016.1 €/MWh, adopting energy bags to store air.

3.3. Sensitivity Analysis

For the San Pietro plant a sensitivity analysis was done in order to evaluate the effects on the plant design of site depth and distance from the coast, and of pipeline inner diameter. But what is more interesting is the economic sensitivity carried out to understand what can contribute to make the plants more convenient and attractive for investment. Since the best way to reduce the LCOS is to increase the plant h_{eq}, the way they are affected by compressor size P_c, margin width around the moving mean PUN and air storage size is investigated. The results obtained for the San Pietro plant in 2019 are shown in Figure 3.3, underling that the major effect on plant h_{eq} is given by the chosen margin width around moving mean PUN. The same trends are obtained for San Pietro and the other two plants for all the three years under consideration.

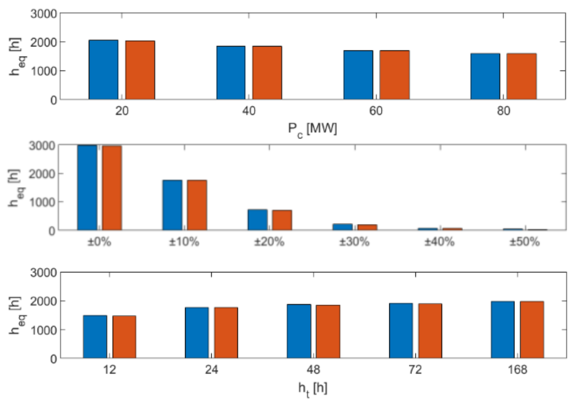

Figure 3.3: From top to bottom for San Pietro plant in 2019: $h_{eq,c}$ (blue) and $h_{eq,t}$ (red) varying P_c, margin around the moving mean PUN and hours of continuous turbine operation.

By reducing the margin to ±0%, the h_{eq} of compressor and turbine rises over 3000 h per year. In 2020, that is the year with the lowest values of LCOS, they result 711.3, 356 and 689.6 €/MWh for the plant of San Pietro, Catanzaro and Trapani respectively, using energy bags.
Furthermore, since the submarine components have a great impact on CAPEX and OPEX, a case without their OPEX and a case with a pipeline length equal to zero were evaluated for San Pietro plant in 2019. In the first case, even if they account for more than 95% of the OPEX, their cancellation still results in operation costs higher than revenues, with a reduction in ~25% of LCOS. In the second case instead, that represents the layout with turbomachines and TES on an off-shore platform, a reduction of 64.8% of LCOS occurs without considering costs related to the off-shore platform.
To complete the analysis, the San Pietro plant is again considered using the electricity prices of Germany in 2019, instead of those of Italy. This is done because they present also values lower than zero, for a total of 211 hours, as well as a lower average annual price. The results are compared in Table 3.2.

Parameter	ITA	DUE
$\boldsymbol{h_{eq,c}}$ **[h]**	1768	1965
$\boldsymbol{h_{eq,t}}$ **[h]**	1756	1957
Revenues [k€]	182.7	517.1
$\boldsymbol{LCOS_{EB}}$ **[€/MWh]**	1168.3	1037.2

Table 3.2: Results of San Pietro plant in 2019 using Italian and German electricity prices.

The effect of the negative prices on the German market is evident. In fact, the compressor worked for 147 hours during negative energy prices, resulting in a remuneration of 110.2 k€.

4. Conclusions

The results obtained by simulating different plants operation using the written model on MatLab, shows the limits of the UW-CAES technology. The high costs related to subsea components, pipeline and air tanks, make the investment unattractive in most cases, suggesting that the choice of the plant location and layout affects its economic feasibility. Obviously, also the energy price trends influence the results, and especially the LCOS, as discussed in previous paragraph.
The different cases analysed with the aim to reduce the LCOS, only in one case bring its value to 356 €/MWh, that is comparable to those of other energy storage systems using battery technologies [5].
The best way to reduce the LCOS is to increase the h_{eq} of turbomachines, and with this aim, other logics of plant operation can be investigated in future works. For example, basing on the moving mean PUN, activation of turbomachines could be considered only if the conditions met in the evaluation hour persist for a certain number of consecutive hours. Or operation for a minimum number of hours could be imposed once a turbomachine is activated.
Then, the salt-oil HX requires a deeper investigation to limit the consumption of thermal energy stored in solar salt.
In addition, more complex plant configurations could be analysed, for example thinking to produce some hydrogen with the energy provided by the WF and burn it after the TES to reach higher inlet turbine temperatures.

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