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Proposal Of Optimized Solutions For Joint Use And Hybridization Of Energy Storage Systems And Combined Cycles Or Renewable Energy Plants

Rafael Olavarria Rodriguez-Arango
Industrial Engineer. Superior Technical School Engineers of Sevilla
Independent Energy Consultant, Sevilla (Spain)

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Abstract

This article describes an electrical energy storage system with a heat pump and steam accumulators or molten salt storage, and solutions are proposed for the hybridization of this storage system with power plants, mainly combined cycle and renewable, already existing or new construction.

As a result of the development of these solutions, it is concluded that these hybridizations allow each one of the plants to operate with its nominal performance in peak hours and with a similar or higher performance in off-peak hours or periods of low prices, that is, , the electrical energy supplied to the network for each thermal or electrical kilowatt that feeds the plants is similar or higher when this electrical energy is previously stored. These high efficiencies after storage are achieved by combining heat pump performance (COP greater than 2) and Rankine cycle heat rate.

In summary, it is possible to optimize the performance of the power plants during all hours of the day and optimize costs due to the joint use of equipment and systems.

Highlights

Hybridization combined cycles, renewables and electricity storage can become a useful tool.

Hybridization can optimize the joint operation of the electrical system.

Proposed hybridization achieves the same performances after storing the energy.
Proposed hybridization allows sharing of equipment and systems.

Keywords: Hybridization; Electrical Energy Storage; Combined Cycle, Renewable Energy; Combined Cycle Renewable Energy; Combined Cycle Energy Storage, Renewable Energy storage; Hybridization Combined cycle renewable

The hybridization of combined cycles, power plants, mainly renewable, and electrical energy storage systems can become a useful tool for the current scenario of continuous growth in electricity consumption and in the participation of renewable energies.

According to the "New Energy Outlook 2019" report (Blomberg New Finance, 2019), the demand for electricity will increase by 62%, between now and 2050, with a production capacity that will triple in the next thirty years.

According to the afore mentioned report, electricity produced from fossil fuels currently represents approximately two-thirds of total production. Within 30 years, the situation will have turned upside down, since renewable sources alone will represent two-thirds of the energy produced on the planet. The protagonists of the change will be solar and wind technologies, the former going from the current 2% of total production to 22% in 2050 and the latter from the current 7% to 26% in thirty years. This solar and wind energy is expected to contribute, in 2050, almost half of the world's electricity consumption (Blomberg New Finance, 2020).

The year 2021 placed exceptional demands on electricity markets around the world. Strong economic growth, combined with colder winters and warmer summers, boosted global electricity demand by more than 6%, the largest increase since the recovery from the financial crisis in 2010 (IEA, 2022).

Renewable energies, mainly wind and photovoltaic, are characterized by their intermittent production, depending on the wind or the sun, so their production does not always coincide with the existing demand and, on the other hand, the locations of these plants, due to the need to have abundant solar irradiation or wind, does not always coincide with the most advantageous locations from the point of view of the needs of the electrical network, which implies significant costs in the transport of this electrical energy.

This increase in electricity consumption, together with the growing penetration of renewable energies, with their intermittency characteristics and specific geographical location, generates significant problems in the electrical network due to the difficulty of meeting the demand peaks and that a balance between offer and demand is achieved, which generates shortages and significant differences in electricity prices between the different hours of the day; and it also hinders the stable and reliable operation of the electrical network.

Because of the above, it is required flexible production systems, with quick start-up and low investment costs that can serve to cover these demand peaks, and electrical energy storage systems that establish a balance between electricity supply and demand and price arbitrage, while increasing the stability and reliability of the network (IRENA, 2017).

Most reports describing future scenarios of the European energy landscape agree that energy storage will be one of the main tools to support the energy transition (Joint EASE-EERA,2013).

IEA report on Energy Storage published in November 2021 points out that "Rapidly scaling up energy storage systems will be critical to address the hour-to-hour variability of wind and solar PV, especially as their share of generation increases rapidly in the Net Zero Emissions by 2050"

In recent years, batteries, mainly lithium, and hydrogen fuel cells, are gaining a key role. In the case of batteries, due to the drastic price reductions that are taking place, and which are expected to increase soon; and in the case of hydrogen cells, due to the expectations that the obtaining of this hydrogen by electrolysis from renewable sources (green hydrogen) is arousing for its use mainly in electric vehicles, but also for other uses.

Large-scale battery storage currently has some drawbacks, including cost and lifetime, or efficiency (75-80%). However, these problems should not be inconvenient for a future implementation if continuous price reductions and technological improvements continue to occur.

But this deployment of batteries for large-scale storage may be affected by the fact that many of its main components, such as lithium, cobalt, or graphite, are relatively scarce compared to the global demand that will probably end up existing, and that they are often extracted from minerals in conflict zones, creating significant environmental and human rights problems (Thomas et al., 2018).

Therefore, it is foreseeable that this progressive reduction in prices may be affected in the future, there may even be shortages, so the uses of these raw materials will probably end up mainly oriented to applications with higher added value, such as their use in transportation or in industrial consumption and, within the storage of electrical energy, to ensure a stable and reliable operation of the electrical network, but, to a much lesser extent, to large-scale storage.

Hydrogen fuel cells are also presented as an important alternative for the substitution of oil and its derivatives as the price of electrical energy produced from renewable energies decreases, and with the aim of replacing current means of transport with electric vehicles, as well as for the production or storage of electric energy on a low and medium scale or emergency, and for other industrial uses (Miller et al.,2020).

But these hydrogen fuel cells also present important problems (high investments, scarce raw materials, low efficiencies, durability, difficulty of storage and transport due to the high pressures and volumes required, and the danger of their use because they are highly flammable), so it is likely that its future implementation, as costs decrease and technological improvements are produced, will take place in uses with high added value, such as electric vehicles and other consumer goods, and not in large-scale energy storage (IRENA, 2018).

In summary, it seems necessary that new electrical energy storage systems appear capable of storing large amounts of energy for extended periods of time and that are profitable.

For this large-scale electrical energy storage (GW) the most viable solutions are currently: Hydroelectric pumping (PH) and Compressed air (CAES systems).

PHS plants have been well tested. There are many plants around the world in commercial operation. Nowadays, these systems have an efficiency between 76% and 85%. They require large land areas in adequate natural sites, which are difficult to locate. For their construction, they require upper and lower water reservoirs and dams, producing large environmental impacts and, therefore, a negative public opinion.

The efficiencies of the CAES systems are of the order of 50%, when gas or other auxiliary fuel is not supplied, and 70% with this contribution of the auxiliary fuel, and require large storage capacities.

This article describes a new storage system that allows to achieve the objectives of storing large amounts of energy for long periods of time, improving the efficiencies of the systems described above, since efficiencies of 100% and higher are achieved, and requiring less high-cost storage capacity (more than 7 times less capacity required than CAES systems) and in less conflictive locations.

However, trying to cover all the peaks in the demand for electricity, when there is no solar or wind irradiation, would force these storage systems to be oversized, significantly increasing the necessary investments.

Consequently, it seems advisable to have flexible systems, which are cheap and quick to start, which complement the electrical energy of the storage systems to cover all the demand peaks. Combined cycles meet the above objectives.

Combined cycles, with their ease of starting, even more so when they can also operate in an open cycle, installing a bypass chimney, and with their relatively low investment, they can solve the first of the problems mentioned: cover the demand peaks. But, even considering its relatively low investment, its operation for only a few hours makes its profitability difficult, especially in a scenario of high natural gas prices.

These low returns on investment are significantly reducing the installed power and the production of combined cycles in the world. Nowhere is this more striking than in Europe where several CCGT plants have closed. This includes Eon's Irsching CCGT plant in southern Germany, even though it was the world's most efficient power plant at the time with a 60.8 percent rating, according to Forbes. The plant was designed for baseload use, and its high combustion temperature and pressures did not allow efficient operation in conjunction with intermittent renewable flows.

As a conclusion to the above, the combined cycle market must evolve towards more flexible operating modes and faster start-ups designs, but it is also necessary, through its hybridization with storage systems, to increase its operating hours so that they are obtained a reasonable return.

Hybridization between combined cycles, renewable energy power plants and electrical energy storage systems can optimize the joint operation of the electrical system, allowing the combined cycles and renewable plants to operate during peak and high electricity prices hours producing electricity directly to the external grid, while in times of low demand and low electricity prices, the electricity produced can be stored to be discharged later, when demand and electricity prices are high. Also, this hybridization allows to increase the load factors of the combined cycles and the prices at which they sell their electricity, increasing their profitability, at the same time, that a more optimized and reliable electrical system is available.

The hybridizations proposed in this article use a storage system with a heat pump, steam accumulators or molten salts.

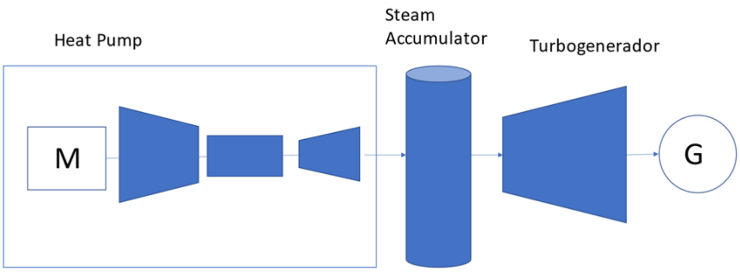

Fig.1 Electrical energy storage system with steam accumulators or molten salt basic scheme

With this storage solution, the proposed hybridization makes it possible for the plants to operate by directly feeding the external network with the same performance as when each one of them is designed to act in isolation; and, also, it achieves that these efficiencies are maintained, or exceed, when the electrical energy is stored and later discharged to the network. In other words, the amount of electrical energy that finally feeds the external network is the same whether the plants are designed to operate in isolation or to be hybridized, and, in this case, whether the energy is stored or not. It can even become higher after going through storage.

Also, the hybridization proposed presents a high flexibility in its configuration, since it allows solutions that take advantage of elements or equipment of the plants for use in the storage system and vice versa and allows its implementation using existing sites and equipment.

1. Description

The proposed solution basically consists of the integration of combined cycle or renewable power plants, or both, or, also, of conventional power plants, with an electrical energy storage system with heat pump and steam accumulators (esheatpac).

Alternatively, it is also possible to choose to replace the storage with heat pump and accumulators by a system with a heat pump and thermal storage with molten salts (OSTI.GOV,2016), which can be especially interesting when the integration is conducted with a thermo solar power plant of molten salt or with a molten salt storage system.

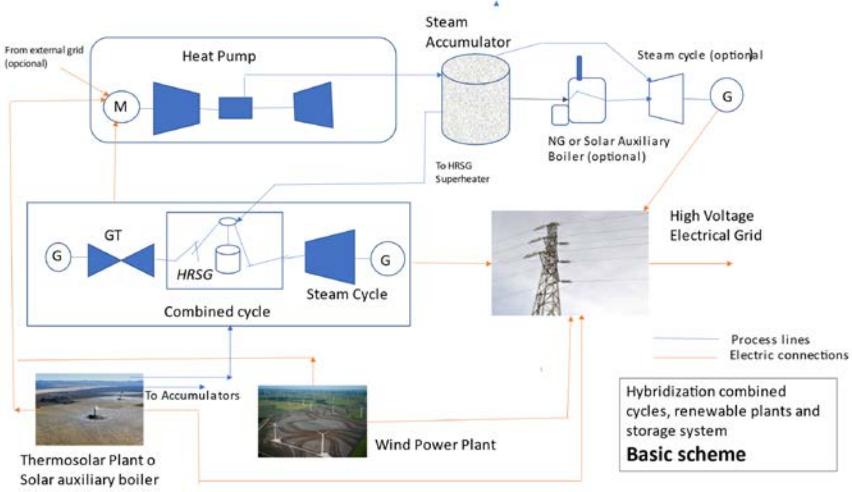

Fig.2 Basic scheme: Hybridization combined cycles, renewables plants and electrical energy storage systems

The hybridization that can be achieved is not limited to the integration of the plants with the storage system, but there are also additional possibilities of hybridization through the common use of steam generation or cooling systems when operating conditions so advise. As an example, cite the use of the combined cycle heat recovery steam generator (HRSG) to superheat the saturated steam generated in the solar field, simplifying the design of the solar field by requiring only saturated steam, or increasing the performance if this solar field is already designed to produce saturated steam; or also, the use of the cold generated in the power plants to optimize the efficiency or COP of the heat pumps.

Any type of power plant that is integrated may be newly built or take advantage of existing power plants. Also, it may be of any type or configuration (combined or conventional thermal cycles of different pressures and overheating, solar tower or parabolic, photovoltaic, wind, biomass, or any other type).

These plants may be in the same location or in various places. Also, the storage system may be in an independent place or in the same place as any of the power plants, preferably next to the combined cycle power plant or the thermal power plants to be able to take advantage of common systems or equipment, mainly the cooling systems.

If the storage system is installed in a location other than all or part of the power plants, its location should be as equidistant as possible from them, weighting the different powers, to reduce losses when operating by feeding the storage system.

These proposed solutions can be dimensioned for any power of each one of the plants, as well as for any storage capacity compatible with the size of the plants.

However, it is estimated that the highest profitability will be found in ranges of high storage capacity, from higher than 10 Mw up to hundreds of megawatts, and medium discharge times (hours).

The proposed electrical energy storage system basically consists of a heat pump whose compressor is driven by electrical energy during periods of low demand or low electricity prices, and which compresses a refrigerant fluid to a temperature at which it is capable of exchanging heat with a stream of water to generate steam, which is stored as high pressure saturated liquid water in steam accumulators; or it is capable of heating molten salts to a temperature that can also generate steam. In periods of high electricity prices or high demand, this liquid water is extracted from accumulators as steam by flash or sudden evaporation. This steam is conducted to a turbogenerator that produces electricity that feeds the external network, closing the charge and discharge cycle. In the case that molten salts are used, these will also exchange heat with the water to generate steam.

The combination of the efficiency of the heat pump (COP higher than 2) and the Rankine cycle, which uses stored steam to generate electricity, makes it possible to achieve efficiencies of 100% or higher.

Ammonia can be used as the refrigerant fluid, but also other refrigerant fluids, such as carbon dioxide, which allow similar efficiencies to be obtained, and are more manageable and economical (Kontomaris et al., 2013).

This storage system has been described in detail in the article published in the European Scientific Journal, January 2020 edition, vol 16, No.3 (Olavarria.,2020).

Basically, combined cycle power plants and any other plant involved in hybridization can feed directly into the external grid producing electricity with their nominal efficiencies during peak hours or high electricity prices, but when demand or the price of the electricity decreases, these power plants feed the compressor of the storage system generating steam that is stored in the accumulators or heating molten salts as explained above, which will later be used to produce electricity for the external grid.

In summary, the basic hybridization solution that is proposed consists of: combined cycle power plants, renewable or conventional power plants, and an electrical energy storage system.

However, this basic solution allows other variants, some of them already commented, that. in some cases, it improves efficiencies and in others, they reduce investment, such as:

A superheating boiler can be installed powered by the same natural gas that feeds the combined cycle, so that the steam coming out of the accumulators is superheated in this boiler. In this case, the efficiencies that can be achieved can exceed 120%.

Also, the saturated steam from the accumulators can be overheated in the HRSG superheater ,as explained above.

The same turbogenerator, steam cycle or cooling system can be used both for the combined cycle and for the discharge of steam from accumulators, with the consequent reduction in material investment.

In the case of a solar thermal power plant, it is possible to choose to install only the solar field, whose steam will feed an oversized combined cycle and the accumulators or molten salts.

2. Operational strategies

A hybridization project such as the one proposed requires high flexibility, with different modes of operation, considering that it must operate in totally different conditions when there is a high demand for electricity (peak hours) or when this demand is low (off- peak hours).

But, also, the configuration or design of each project must consider different operating alternatives depending on aspects such as the convenience of optimizing the operation to obtain maximum production, when electricity prices are very high, or, on the contrary, optimize the operation to obtain maximum performance; or, also, the convenience of installing a reinforcement with natural gas or another auxiliary fuel, depending on the availability and price of this fuel and the price of electricity at all times. As an example, we list different alternatives that should be considered when designing each hybridization project:

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Normally, in periods of high demand, combined cycles or renewable plants will feed directly to the external electricity grid, but also, during these hours, the steam that has been stored in the accumulators during periods of low demand, such as saturated water at high pressures , it can be unloaded, feeding the steam turbine of the combined cycle, which will be oversized. This injection of steam in the combined cycle can be directly as saturated steam, or it can be as superheated steam after this saturated steam is superheated or reheated in the heat recovery boiler of the combined cycle, or by the same accumulator system, or by an auxiliary boiler, before being injected into the combined cycle steam turbine.

If the storage is with molten salts, during peak hours the salts that have been heated during off-peak hours will also generate steam that will feed the existing steam turbines as described above. In this case, superheated steam can be generated directly, not requiring superheating solutions with boilers.

Thus, during peak hours, the power discharged to the external grid will be maximum, adding to that produced by the combined cycles and renewable or conventional power plants, which coming from the storage system.

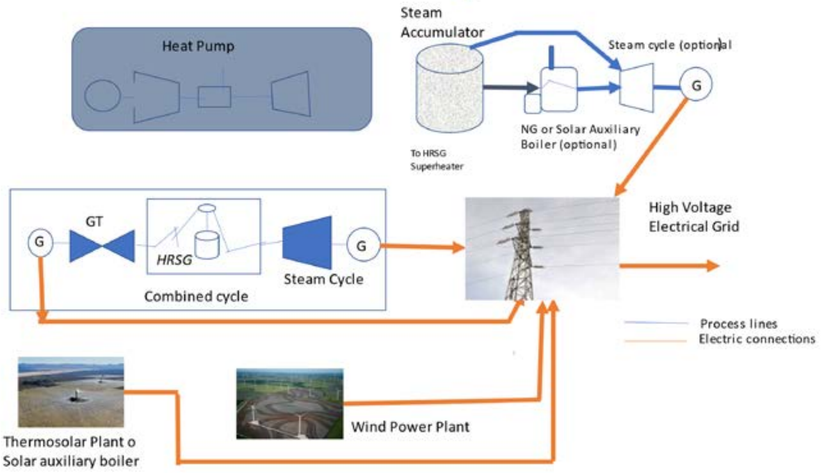

Fig.3 Operation strategy: Peak hours

During off-peak hours, the power plants may power to the electrical motor of the heat pump compressor to generate the steam or heat molten salts. This electrical motor can also be powered by the external electrical grid taking advantage of the low price of electricity if this is of interest.

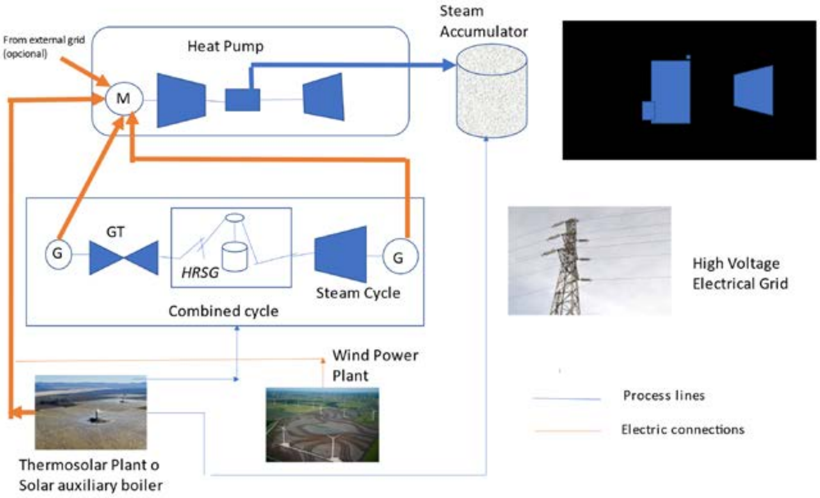

Fig.4 Operation strategy: Off-peak hours (100% storage)

The solar thermal power plant may or may not have its own steam turbine and steam cycle. If it does not have your own steam turbine or steam cycle, which means a cheaper solution, it can during charging periods (off-peak hours) feed directly to the steam accumulators or to molten salts, and during peak hours feed to any of the steam cycles that it shall be oversized. In these cases, this solar thermal power plant cannot directly power the electrical motor of the heat pump compressor.

Obviously, intermediate situations can be considered, both in the design and in the operation strategies, so that only part of the electricity generated by the plants, during off-peak hours, can be used for storage and the rest will feed directly to the external grid.

3. Expected performances

During peak hours, the combined cycle and the renewable or conventional power plants will feed the external electricity grid with their respective nominal efficiencies, which, in the case of combined cycles, can reach 60% or higher efficiencies.

During off-peak hours, combined cycles and renewable or conventional plants will feed the storage system, subsequently producing electricity at peak hours.

The performance that can be obtained in these off-peak hours will be the product of the performance or heat rate of the plant involved by the performance of the storage system.

4.1. Storage system performances

The performance of the Esheatpac system is calculated by the division between the electrical energy produced by the turbogenerator and the electrical energy of the system's inlet. This electrical energy of the system's inlet is the sum of the required energy to power the compressor motor and the energy to power the feedwater pump. The total electricity produced by the turbogenerator is calculated by the electrical energy produced in the generator outlet minus the electrical energy required to operate the condensate pump.

In the Esheatpac, the heat pump performs a similar function than a boiler in a conventional thermal electric plant. Therefore, it is possible to define the efficiency of this system as the product of the heat pump efficiency (COP) and the efficiency of the water-steam cycle (Rankine cycle efficiency or heat rate) designed to produce the outlet system electrical energy, using the steam stored in the accumulators as pressurized water.

The heat pump COP is the percentage or relation between heating provided by the heat pump and electricity consumed by the heat pump.

The heat pump COP is higher than 1 (or 100%) because the heat pump is moving heat by using energy, instead of producing heat as electrical resistance. A significant part of this heat is supplied by ambient air enthalpy or by a waste heat source, such as the hot water from the condenser cooling system.

For every heat pump, the heat transferred to heat sink is the sum of the heat extracted from the heat source and the energy consumed in the compressor, transmitted to the heat pump fluid, minus the energy produced in the expansion turbines, transmitted to the compressor shaft. This energy produced in the expansion turbines is the waste energy from the heat pump fluid after providing heat at the heat source, and before being conducted to the heat sink.

$QC = QF+WC-WX$, where:

(1)

QC is heat given to heat sink; QF is heat from heat source; WC is compressor work; and WX is expansion work.

In accordance with the COP definition (relation between provided heat and consumed electricity), the COP of the proposed electrical storage system is:

$COP = QC/(WC-WX) = (QF+WC-WX)/(WC-WX) > 1$

(2)

QC is the heat given by compressed fluid to the steam generator to produce saturated steam, which is stored in accumulators as pressurized or compressed liquid water.

QF is the heat from ambient air, or from a waste heat source, or from the condenser cooling water. It is used to evaporate and preheat liquid, or partially evaporate the heat pump fluid, at temperature lower than ambient air temperature after expansion stages.

The more heat can be extracted from the ambient air, or from other waste source, the higher the heat pump COP.

From a theoretical point of view, the heat pump COP, operating as a heat source, depends on heat source and heat sink temperatures, in accordance with the following equation:

$COP = 1 /(1-(T2/T1))$, where: (3)

T2: Heat source absolute temperature.

T1: Heat sink absolute temperature.

This COP represents the maximum theoretical value, which is 14.65 when the external temperature is 0 °C, and the internal temperature is 20 °C. In other words, it is possible to generate 14.65 thermal kilowatts for each electrical kilowatt consumed, from a theoretical point of view.

The heat sink temperature proposed by the Esheatpac system depends on feedwater pressure, the temperature (saturated temperature) required to generate steam at elevated pressure, and the temperature to produce electricity at reasonable Rankine cycle efficiency. This temperature is higher than the above referenced 20 °C.

In a theoretical calculation, it is possible to achieve a heat pump COP around 3, generating steam at around 100 bars. This steam can operate with a high Rankine cycle efficiency.

There are multiple power plants in the world operating with Rankine cycles and their efficiencies or heat rates are well known and proven.

The efficiency of a Rankine cycle with saturated steam is approximately 38%, and that of a cycle with superheated and reheated steam reaches 47%, as is well known.

As a result, the efficiency of the Esheatpac system is higher than 141% when the heat pump COP is 3 and the Rankine cycle efficiency is 47%. In other words, the inlet electrical energy is multiplied by 1.41 to match the outlet electrical energy.

From a practical point of view, considering the requirements of ammonia or carbon dioxide as a fluid, the maximum foreseen heat pump efficiency is around 2.65, including losses.

Therefore, efficiency reaches up to 100,7% when the heat pump COP and saturated steam Rankine cycle efficiencies are above the referenced values of 2.65 and 38%. When the superheated and intermediate reheated steam are present in the Rankine cycle, the cycle efficiency is higher than the referenced value of 47%. Thus, the efficiency of the Esheatpac reaches 124,5%.

4.2. Hybridization's performances

In the case of combined cycle plants, the resulting performance will be the product of the combined cycle heat rate (60% or higher) and the performance of the storage system, which can reach 100.7%, without the need to add auxiliary fuel, as a result of multiplying the COP of the heat pump (2.65) by the heat rate of the Rankine cycle operating with saturated steam (38%).The final result or resulting performance will be 60.4%, slightly higher than the nominal of the combined cycle when it operates directly connected to the grid at peak hours

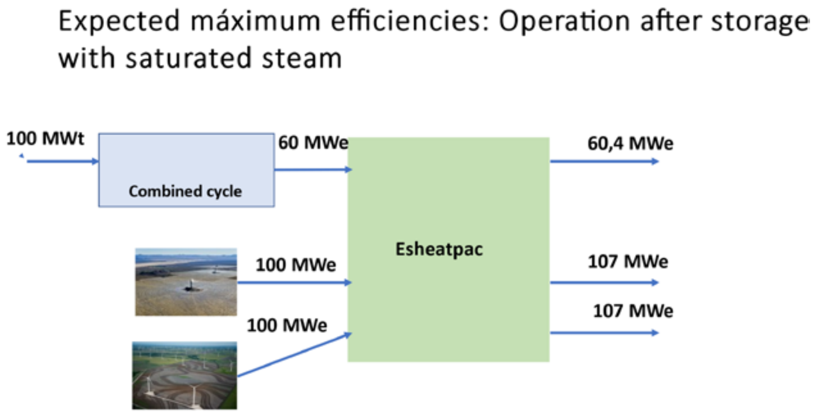

Fig. 5A Expected maximum efficiencies: Operation after storage with saturated steam

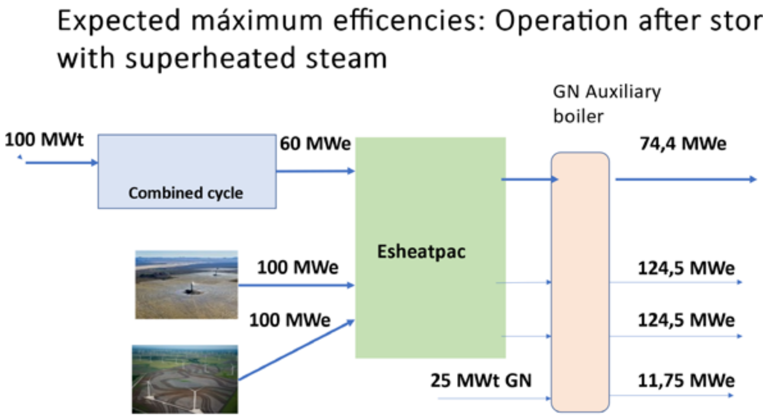

Fig. 5B Expected maximum efficiencies: Operation after storage with superheated steam

If auxiliary fuel is supplied to superheat the saturated steam that comes out of the accumulators of the storage system, or without the need for this input in the case that the storage is with molten salts, the resulting efficiency can reach 74.4% , because of the increase in the heat rate of the Rankine cycle to 47%. In this assumption of contribution of fuel, this will produce electricity with the efficiency of the Rankine cycle (47%), and the overall efficiency considering the combined cycle and the fuel supplied may reach 67.6%. In all cases, higher efficiencies than those obtained from the combined cycle at peak hours producing directly to the external grid.

In the case of conventional plants, these efficiencies will decrease because of the lower heat rate of these plants compared to combined cycles.

The wind power plants will feed the storage system with the electricity they produce in accordance with their nominal efficiencies that may exist at any given time, and each Kwh contributed will produce 1.07 kwh to the external grid, without the contribution of auxiliary fuel, and 1,245 kwh to the external grid with the contribution of fuel.

As previously indicated, alternative solutions can be proposed seeking a lower investment, for example, by overheating the saturated steam from accumulators in the HRSG superheater of the combined cycle; or with installing of a solar thermal power plant without steam cycle.

In the case of overheating the steam in the combined cycle, superheater must be oversized. This oversizing does not have to affect the heat rate of the combined cycle operating to feed directly to the external grid, but it will decrease the heat rate when operating simultaneously from accumulators, since the same exhaust gases from the gas turbine will have to overheat a greater amount of steam. This loss of heat rate that occurs will depend on the amount of steam generated in accumulators.

In the case of a solar thermal power plant without steam cycle, electricity from this plant cannot feed directly to the external grid or to the motor compressor. At peak hours , the steam generated at this plant will be derived to the combined cycle , which must be oversized, and performance will be practically not affected. In off-peak hours, the steam generated in the plant will feed directly to the steam accumulators, the efficiency of the electricity obtained will be that of the steam cycle heat rate, that is, on the order of 38% maximum, if the steam turbine is saturated steam, and 47% if the steam overheat in an auxiliary boiler or HRSG combined cycle.

4. Practical case

Following, we present the specifications and main conclusions of two cases. The specifications of both cases are identical, with the only difference that in one case the storage system generates saturated steam and, in the other case, superheated, and therefore each Rankine cycle and each steam turbine are specified for each of these steam conditions.

As a reference, we use a high-performance combined cycle, such as a combined cycle with high use of the exhaust gases of an M701G gas turbine, which would give us a nominal combined cycle performance of the order of 59.3% according to reference from manufacturers.

We connect this combined cycle to a storage system (Esheatpac system) consisting of a two-stage compressor, with an inlet pressure of 1 bar and an outlet pressure of 110 bar (absolute bar in all cases) and an efficiency of 92%; a steam generator capable of generating steam at a pressure of 200 bar; and a three-stage expansion turbine, with intermediate evaporations in each stage and after the final stage, with outlet conditions of 1 bar and minus 30ºC, and a 90% efficiency. Ammonia is used as the heat pump fluid (Lester et al., 2018)

The steam generated in the generator of heat pump will feed an accumulator that can be made, depending on the required storage capacity, with steel carbon, or steel pipes maximum diameter and high strength (X80 / X90), or they can be built of prestressed concrete, in case of large storage capacities are required.

During the discharge periods, the saturated steam stored in the accumulators will feed a steam turbine, with an inlet pressure of 100 bar and a vacuum pressure of 0.025 bar.

If overheating is chosen, the inlet and vacuum pressures will be maintained, and the overheating will reach a temperature of 585ºC. This overheating will be conducted with an auxiliary natural gas boiler, with an efficiency of 98%.

The main specifications of this practical case are summarized below:

Combined cycle with gas turbine M701

- Power: 500 Mw
- Heat rate: 59,3%
- Pressure: 147 bar

Heat Pump

Compressor

- Inlet pressure: 1 bar
- Outlet pressure: 110 bar
- Efficiency: 92%

Steam Generator

- Saturated steam at 200 bar

Expansion turbines: Three (3) stages with intermediate and final evaporators

- Outlet pressure: 1 bar
- Outlet temperature: -30ºC
- Efficiency: 90%

Steam Accumulators

- Charging pressure: 300 bar
- Discharge pressure: 100 bar
- Insulation: Loss of 1% of its thermal capacity stored in a period of eight (8) hours

Optional turbine: Saturated steam

- Inlet pressure in the steam turbine: 100 bar
- Vacuum pressure: 0,025 bar

Optional turbine: Superheated steam
- Inlet pressure: 100 bar
- Inlet temperature: 585ºC
- Outlet pressure: 0,025 bar

Natural gas auxiliary boiler
- Efficiency: 98%
- Percentage of thermal energy supplied: 25%

Considering the previous basic specifications, the performances or heat rate obtained are the following:

When the combined cycle operates feeding the external grid, its performance will be the nominal of this combined cycle (59.3%, according to manufacturers' references).

It should be noted that in all cases we are talking about nominal efficiencies or heat rates, so in each project and at each moment of its operation, these efficiencies may be different depending on numerous factors, such as cycle configuration, environmental conditions, cooling system, operating conditions, etc.

When the combined cycle feeds the storage system to later feed the turbine with saturated steam and produce electricity for the external grid, the efficiency will be reduced up to 52.5%, since the combined cycle heat rate will remain the nominal 59.5%, but the electricity generated after passing through a storage system with COP equal to 2.46 and a saturated steam cycle of 36%, will be reduced until reaching this performance of 52.5%.

If the saturated steam coming out of the accumulators is overheated by the auxiliary boiler, the thermal cycle performance will rise to 45%, so the previous performance of 52.5% will rise to 65.6 %. In calculating this performance, both the thermal power provided to the combined cycle and that provided to the auxiliary boiler have been considered (“overall performance”).

If the heat pump compressor is powered by a wind power plant, the power generated by this wind power plant, after passing through the storage system with saturated steam, with a COP of 2.46 and a thermal cycle heat rate of 36%, will be reduced to 0.885, that is, each kW of power generated by the wind power plant will feed 0.885 kW to the grid.

As it is logical to deduce, if the storage system generates superheated steam, the efficiency will rise, because of the improvement in the Rankine cycle, up to 1.107, that is, 1.107 kW of power will feed to the external grid for each kW of power generated by the wind power plant. However, in this case, thermal power will also have been provided to the auxiliary boiler, which will produce electricity for the external grid, with an efficiency equal to that of the superheated Rankine cycle (45%). In this case, an overall performance can also be defined as “power generated to the external electrical grid divided by

the electrical power received from wind power plants plus the thermal power supplied to the auxiliary boiler.” This overall efficiency would be 94.2%.
The same results would be obtained if the heat pump compressor is powered by the external grid instead of by the wind power plant.
Next, we summarize the different performances, efficiencies or heat rates that can be obtained according to this practical case:

- Combined cycle generating directly to the external grid: 59,3 (according to supplier information)
- Combined cycle operation after storage with saturated steam: 52,5%, (because of multiplication of the following efficiencies or heat rates):
    - Combined cycle: 59,3%
    - COP heat pump: 2,46
    - Steam cycle heat rate: 36%
- Combined cycle operation after storage with superheated steam: 65,6%, (because of multiplication of the following efficiencies or heat rates):
    - Combined cycle: 59,3%
    - COP heat pump: 2,46
    - Steam cycle heat rate: 36%
    - Overall performance: 60,5%
- Wind plant operation after storage with saturated steam: 0,885- Kilowatt electric sent to the external grid per kilowatt electric sent to the storage system by renewable power plants or external grid
- Wind plant operation after storage with superheated steam: 1,107 (Kilowatt electric sent to the external grid per kilowatt electric sent to the storage system by renewable power plants or external grid)
- Overall performance with renewable plant or external grid: 0,94

Overall performances are defined as : Power generated to external grid divided by the sum of the thermal power supplied to the combined cycle (or by the electrical power received from the renewable plants or external grid) plus the thermal power supplied by auxiliary boilers.
These performances or heat rates may have small variations because of the differences that may exist between the performances of the different equipment for varied sizes.

5. Conclusions

This article describes a new storage system that stores large amounts of electrical energy for long periods of time, improving the efficiency of existing systems (up to 100% efficiency or higher) and requiring less conflictive locations and lower storage capacities per Kilowatt stored.

Also, solutions are presented for the joint use and hybridization of this storage system with new or existing power plants, mainly combined cycles, so that it is not only possible

to store energy to balance the supply and demand of the electrical system with efficiencies not achieved to date, it also allows optimizing the operation of these plants at different times of the day, increasing their profitability, as well as reducing investments through the joint use of systems or equipments. Finally, a more stable and reliable operation of the electrical network is achieved.

Alternative solutions are presented aimed at obtaining maximum efficiencies or optimization of the necessary investment.

In summary, we are talking about a solution that can help with the important challenges that electricity currently faces.

In the development of this work, the balances, and calculations to justify the results obtained have been carried out. Subsequent work should be aimed at further developing and optimizing the proposed solutions, as well as conducting tests or pilot plants to ensure the viability of the solutions before their final commercial implementation.

Also, collaborations with equipment manufacturers to ensure the suitability of their equipment to reach the conditions required by this storage system are necessary.

Especially important are the collaborations and tests of compressors to ensure that ammonia or carbon dioxide can reach the required conditions; and, to continue with the research and tests already underway to develop prestressed concrete tanks with very large capacities and molten salts with high heat capacity and phase changes.

Prestressed concrete tanks, molten salts and compressors are key elements for the implementation of the Esheatpac storage system and its hybridization with power plants.

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