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Research Article

Levelized cost of energy and storage of compressed air energy storage with wind and solar plants in Morocco

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ABSTRACT

To reduce greenhouse gas emissions and the environmental impact of fossil fuels, Morocco has decided to increase the use of renewable energy resources. The intermittent nature of renewable energy resources causes instability in the power grid. Energy storage is the appropriate solution to this problem. Compressed air energy storage is a technology that stores energy in the form of high-pressure compressed air in above ground tanks or underground caverns. Large-scale storage of compressed air energy requires the storage of large volumes in salt caverns or aquifers. The aim of this paper is to find out the benefits of integrating underground compressed air energy storage technology. A case study in Morocco is used to estimate the levelized cost of energy plus storage (LCOES). The annual capacity factor for solar and wind power plants and the potential of underground caverns in Morocco were analyzed. The results illustrate that for a system with 100 MW capacity installed in the Casablanca region, the combination of an adiabatic compressed air energy storage system (ACAES) with a wind turbine installation offers the lowest electricity price per kWh, with average LCOES of 0.04 $/kWh.

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INTRODUCTION

The 2015 International Energy Agency (IEA) report mentions that energy demand has increased due to population growth and technological developments. The percentage of energy generated from fossil fuels presents about 84 % [1]. As a result, a significant amount of greenhouse gas emissions is released into the atmosphere and the improvement of investment costs [2]. The increased use of renewable energy, especially wind and solar technologies, will certainly reduce greenhouse gas emissions and retain sustainable energy. Unfortunately, these technologies are characterized by their intermittent nature, which negatively affects the balance of energy flow and leads to disruption of the power grid. This problem can be solved by storing energy. Since there is no method to store energy in electrical form, energy can be stored in various forms: chemical,

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mechanical, hydraulic, electrostatic, ... One of the most promising technologies for large-scale energy storage is compressed air energy storage (CAES), which can use both underground and above-ground storage. Nowadays, this technology is still under development, and numerous studies have been conducted to improve its global efficiency. Compressed air is generated using devices called compressors, which increase the pressure of ambient air by reducing its volume. If a compressor is used, the electrical energy required to operate it can be obtained from many sources such as the power grid or renewable energies. In our case, the energy used to compress air is generated either by solar or wind sources.

The storage of energy in the form of compressed air began in the 1940s [3]. Nowadays, this storage technology has undergone many improvements to achieve high performance and energy yield. Therefore, reaches the highest system efficiency.

CAES systems work by compressing air into storage during off-peak times when energy demand is low. This stored compressed air is then released and expanded through turbines to generate electricity during peak demand periods, helping to balance the grid.

There are three types of compressed air storage technologies and some other derivatives. The first version is the diabatic CAES. It is also called a conventional or classical compressed air energy storage system (DCAES) [4]. The operating principle of a classical CAES is based on storing the excess energy generated by the power plant to be used later when the energy demand is higher than the generation. And, when the demand is lower than the generation, the excess energy is used to compress the air by the compressor and then stored in an underground cavern or in above-ground tanks. Conversely, the compressed air is released and sent to the gas turbines to produce mechanical energy, which is then converted into electrical energy by a generator. Conventional CAES are the first generation of compressed air energy storage, it is known for its low efficiency which is less than 50% [5]. There are two reasons for the low efficiency of DCAES: First, a large amount of heat is released to the atmosphere during the charging process. Second, a large amount of fuel is required during the discharge process to reheat the compressed air to prevent damage to the gas turbine blades. The use of fossil fuels poses a real threat as it releases a large amount of greenhouse gas emissions.

The second version of the CAES system is the adiabatic compressed air energy storage system (ACAES). The innovative idea of the adiabatic version is to recover the compression heat released during the charging process and reuse it during the discharging process. This reduces dependence on fuel and leads to a reduction in greenhouse gas emissions and an improvement in system efficiency. The efficiency of the system is between 60 and 70% [6].

The difference between the two main CAES derivatives diabatic and adiabatic compressed air energy storage (CAES) systems lies in their heat exchange during the compression and expansion processes. Diabatic system involve heat exchange with the surroundings, while adiabatic systems minimize heat exchange to achieve higher efficiency.

The third generation is the isothermal compressed air energy storage system (ICAES). The basic idea of this CAES derivative is to reduce the heat energy loss by slowly cooling the air during the compression process to maintain the temperature constant, while recycling the compression heat in the discharge process to keep the temperature expansion constant. The expected efficiency for this version is over 80% [7]. Slowly cooling the air during the compression process can be practically achieved by using intercoolers, which are heat exchangers that remove heat from the compressed air between stages of compression. This helps to prevent excessive temperature rise and improve system efficiency. In addition, there are other derivatives of the CAES system, such as Liquid Air Energy Storage (LAES), in which compressed air is stored in a liquid state, and Underwater Compressed Air Energy Storage (UW-CAES), and Steam Injection Compressed Air Energy Storage (SI-CAES).

Today, some technical and economic problems have delayed the commercialization of CAES system in many countries around the world. The first technical problem is the overall efficiency of the system, which is around 60%, while the ideal efficiency is expected to be about 90%, which means an efficiency gap of 30%. The second problem is related to the geological conditions for underground compressed air storage. Abandoned mine tunnels and cavities are the most promising solution for large-scale compressed air energy storage. The third problem is the high cost of artificial air storage or surface storage in areas without underground salt caverns or mine tunnels.

The combination of solar or wind turbine technology involves integrating these renewable energy sources with CAES storage system. Excess energy generated by solar panels or wind turbines can be stored for use when the energy production is lower, using compressors.

Tiago Filho et al. [8] analyzed the feasibility of implementing a conventional compressed air storage system in conjunction with a wind turbine in inland Brazil. The analysis includes technical and economic challenges. The study shows that the economic results are unviable for two reasons: There is no suitable location to store compressed air, and the air mass flow in the area is insufficient. The LCOE of the compressed air system associated with the wind farm is 5,107.77 $/MWh, which is a very high energy cost, so implementing this type of system in the area would not be profitable.

S. Sadeghi and I. B. Askari [9] studied a techno-economic system consisting of photovoltaic, fuel cell, batteries, and Compressed Air Energy Storage. The system was designed to fulfill the energy needs of 500 households with a peak electricity demand of 500 KW in Mahan, Iran. Technical and economic analysis was performed to meet the energy demand of the entire houses and to optimize the energy flow in the system. The results have shown a LCOE of 0.2 $/kWh for a pressure output of 12 bar. The proposed system has shown a LCOE values more realistic than the value obtained in the previous results. Nevertheless, the system shows a significant return on investment and its implementation would certainly assist to optimize and minimize electricity costs at this site.

Dib et al. [10] proposed a novel numerical modelling system consisting of a micro advanced adiabatic compressed air energy storage system (AACAES) coupled with a solar power plant. The main objective of the proposed system is to meet the energy demand of a building located in Nice, France. A thermo-economic analysis was carried out to find out the benefits of the system to the energy balance of the building. The LCOE obtained in this study is 1.84 $/kWh. The LCOE analysis in this work has shown unacceptable values that are extremely close to the first study. Otherwise, the system is capable of meeting the energy needs of the building.

Bennett et al. [11] studied the techno-economic aspect of an offshore energy facility consisting of an isothermal compressed air energy storage system with a saline aquifer in conjunction with wind power. This study includes an estimation of the cost and system efficiency on the Atlantic coast of the United States. The system capacity ranges from 10 to 390 MW, and with a capacity of 350 MW, the LCOE of the systems obtained is 0.22$/kWh. The studied combination of wind energy with an ocean compressed air energy storage (OCAEN) shows a significant return on investment, increasing from 0.031 $/kWh (without storage) to 0.048 $/kWh. Therefore, the study proves the feasibility of implementing this combination on the Atlantic coast of the United States.

Cheekatamarla et al. [12] implemented a novel storage system based on near isothermal compressed air energy integrated into residential and commercial buildings. The results show that the reduction in the capital cost of the system leads to a significant change in LCOE, in which it ranges from 0.13$/kWh to 0.07$/kWh. Thus, the system demonstrates that it is capable of controlling both the energy balance and electricity prices at this site.

Abdulrahim and Ahmed [13] conducted an analysis of the levelized cost for a plant consisting of a PV installation to provide energy to a desalination station. The LCOE obtained ranged from 8.46 to 9.11 c$/kWh.

Xu et al. [14] conducted a study on the levelized cost of storage for battery technology in the Chinese context. The cost obtained ranged from 0.12to0.17 per kWh.

The primary objective of this paper is to examine the levelized cost of energy and storage across various scenarios. This study employs compressed air energy storage (CAES) technology in conjunction with energy sources such as solar or wind plants. Notably, the distinguishing factors between this research and the cited articles lie in the choice of storage technology and the geographical context, as no prior study has explored the potential and feasibility of utilizing CAES technology in Morocco.

In this article, a brief introduction of the different derivatives of CAES technology is given, followed by a feasibility analysis of the integration of CAES technology for the case of Casablanca region in combination with solar or wind turbine technology. A brief description of the main salt mine in Morocco, which is the most suitable for the storage of energy in the form of compressed air. Finally, the last part of the paper discusses and analyzes the results of the LCOE, LCOS and LCOES.

METHOD

The methodology adopted in the present paper involves sourcing all data from existing literature and new data obtained from different sources such as the data on the annual capacity factor and data on the available space able to store compressed air.

Potential of Underground Compressed Energy Storage in Morocco

There are only a few sites that could be considered for CAES underground storage in Morocco because compressed air storage requires specific geologic criteria to determine the suitability of an area. Firstly, the identification of hard or porous rock geologies, four rocks have been shown to be suitable for underground storage when combined with aquifers and natural gas tanks to form caverns. These rocks are mixed sedimentary rock, carbonate sedimentary rock, acid plutonic rock, and siliciclastic sedimentary rock [15]. Second, the locations of salt caverns for the Moroccan state were gathered and used to estimate the amount of energy storage in these areas. In this section, a detailed description of the main salt caverns in Morocco is given. Third, compressed air can be stored in a large aquifer system.

An estimation of the available volume is calculated based on three factors: Salt production rate, salt density, and year of exploitation. This estimation has been made due to the unavailability of information related to salt caverns in Morocco. The volumetric density of the salt is equal to 2.15 g/cm3 [16] and the period of exploitation is estimated to be about 30 years.

The most important salt cavern in Morocco is located in the southeast of Mohammadia and is known by the name of the Ain Tekki mine. The salt deposit extends for 80 km (from Berrechid to Mohammedia) with a depth of over 500 m. The Mohammedia salt mine covers an area of 1,500 km², which would make it a good option for underground storage of energy, especially compressed air, hydrogen and liquefied natural gas. Currently, two projects are underway to store energy in this cavern: Hydrogen and liquefied natural gas (LNG) [17].

The Tissa salt mine in Taounate province started in 1996 with an average production rate of 10850 tons of salt per year [18].

Annual Capacity Factor

The annual capacity factor is defined as the energy generated annually by a given plant divided by the plant's power capacity in a given period [19]. In other words, it measures the power plant energy output compared to the maximum power could the power plant generate in a given period without interruption. The following mathematical formula of the annual capacity factor is given by the equation 1.

$$AFC_{w,s} = \frac{E_{w,s}}{365*24*P_{w,s}} \quad (1)$$

Where Ew,s and Pw,s are respectively the annual energy generated by the power plant and the power rated of the plant. The annual capacity factor was calculated using the Renewables Ninja website [20]. The input data for the solar and wind technologies are shown in Table 1 and Table 2.

Levelized Cost of Energy

Levelized Cost of Energy (LCOE) is often cited as a practical measure of the overall competitiveness of various electricity generation technologies. For the energy researchers, LCOE is an important key to choose between different technologies. It helps in selecting the most suitable, profitable, and efficient technology [21]. LCOE is the price of electricity per kWh or MWh to build, operate, and maintain a power plant over the financial lifetime or operating cycle of the project, divided by the amount of energy generated by the plant. LCOEs are affected by specific technological and regional factors, particularly energy taxes and emissions levies imposed in each country or region. The mathematical approach to estimating LCOE and LCOS are given in Equation 2 and 3.

$$LCOE = \frac{CAPEX + \sum \frac{(O\&M+Fuel)_t}{(1+r)^t}}{\sum \frac{(Annual\ Energy\ Produced)_t}{(1+r)^t}} \quad (2)$$

$$LCOS = \frac{CAPEX + \sum \frac{(O\&M+Fuel)_t}{(1+r)^t}}{\sum \frac{(Annual\ Energy\ Produced*\eta_{CAES})_t}{(1+r)^t}} \quad (3)$$

Where CAPEX is the capital cost, OM is operation and maintenance costs, r is the discount rate. The LCOE input data are given in Table 3, and the plant capacity is assumed to be 100 MW.

The integration of storage systems will certainly have an impact on the cost of electricity. Therefore, the formula is changed to include the parameters of the storage system. The new term is called levelized cost of energy plus storage (LCOES). The LCOES calculations of each combination are given in the equations 4, 5 and 6.

$$LCOES = \frac{CAPEX_{PV,Wind,CAES} + \sum \frac{(O\&M+Fuel)_t}{(1+r)^t}}{\sum \frac{(Annual\ Energy\ Produced*\eta_{CAES})_t}{(1+r)^t}} \quad (4)$$

$$LCOES_{PV,Wind,DCAES} = \frac{CAPEX_{PV,Wind,DCAES} + \sum \frac{(O\&M+Fuel)_t}{(1+r)^t}}{\sum \frac{(Annual\ Energy\ Produced*\eta_{CAES})_t}{(1+r)^t}} \quad (5)$$

Table 1. Input data for solar plant

Parameter	Value
Localization	Casablanca (33.5951,-7.6188)
Capacity [MW]	20
System loss [fraction]	0.1
Tracking [-]	None
Tilt [°]	35
Azimuth [°]	180

Table 2. Input data for wind plant

Parameter	Value
Localization	Casablanca (33.5951,-7.6188)
Capacity [MW]	20
Hub height [m]	80
Turbine model [-]	Vestas V90 20000

Table 3. The input data for LCOES calculations

Parameter	Solar [22]	Wind [23]	CAES [24][25]
Capital cost [$/kW]	1000-1500	1300	450 + 25% thermal storage (A-CAES)
O&M cost [$/kW]	10	42-45	1+fuel cost (D-CAES)
Energy production[kWh]	172315438	556819339	Energy*η_{CAES}
Degradation rate [%]	0.5	1.6	0.14
Lifetime [years]	25	25	30
Discount rate [%]	5	6	6

$$LCOES_{PV,Wind,ACAES} = \frac{CAPEX_{PV,Wind,ACAES,TES} + \sum \frac{(O\&M+Fuel)_t}{(1+r)^t}}{\sum \frac{(Annual\ Energy\ Produced * \eta_{CAES})_t}{(1+r)^t}} \quad (6)$$

Where ηcaes is the compressed air energy storage efficiency. In the case of DCAES, fuel costs are added due to the dependence on fossil fuels to heat the compressed air, where the average world price of natural gas is 0.078$/kWh.

While, in the case of ACAES, there is no need to use fossil fuels, however it is necessary to add the price of thermal energy storage to the capital cost. The average efficiencies of DCAES and ACAES are 45 and 65%, respectively [26].

In the next part, the results show an overview of the LCOE of each technology, including the two CAES systems. In addition to the LCOES of the wind-CAES and solar-CAES combination. The results of the Levelized Cost of Electricity (LCOE), Levelized Cost of Storage (LCOS), and Levelized Cost of Energy Storage (LCOES) are typically obtained through financial and economic analysis that considers factors such as capital costs, operational costs, interest rates, and the expected lifetime of the system. Matlab software using the equation cited in this paper has done the calculation of these terms. An estimation of total volume to store compressed air is given in Table 4.

Table 4. Available volume for underground storage

Salt cavern location	Volume available (m^3)
Ain Tekki	$3.225*10^{13}$
Tissa	$3.689*10^{9}$
Total volume	$3.225*10^{13}$
Volume Huntorf cavern [19]	141, 000
Possible number of Huntorf cavern	$2.2*10^{8}$

RESULTS AND DISCUSSION

In order to determine the energy equivalent that the total available volume can store. The CAES energy storage density is used to estimate the equivalent energy stored is equal to 0.003M W h/m3 [23]. Therefore, the expected energy storage is about 9.67 TWh. The expected energy consumption in Morocco in 2030 is about 95 TWh [27], which means that the available volume can meet 1017 times the energy demand. Therefore, only 0.1% of the total volume can be used to meet the energy needs of Moroccan citizens and industry.

The annual capacity factor (ACF) for solar and wind technologies are shown in Figure 1 and Figure 2, respectively. Both cases were calculated for a plant to be located near the Ain Tekki salt cavern. The results have shown that the highest ACFs for the solar plant are obtained in the summer period, when the irradiation reaches its maximum values, while the ACFs for the wind plant are obtained in spring and winter.

The annual capacity factor is a metric used to measure the efficiency and utilization of a power generation or energy storage system over a year. It is expressed as a percentage and represents the ratio of the actual energy output of the system to its maximum possible output if it were operating at full capacity continuously throughout the year.

The average ACFs of solar and wind installations are 20.9 and 19.7%, respectively. The results demonstrate the utility of increasing the use of renewable energy in Morocco's energy mix, especially in the Casablanca region. As it known Casablanca is the economic capital; it is therefore hosts the most of Morocco's industry. Conversely, it is also responsible of huge amount greenhouse gas emissions. This type of technology would certainly have a positive impact on the environment in this region.

The monthly energy yield of a solar plant with a capacity of 100 MW in the region of Casablanca is shown in Figure 3.

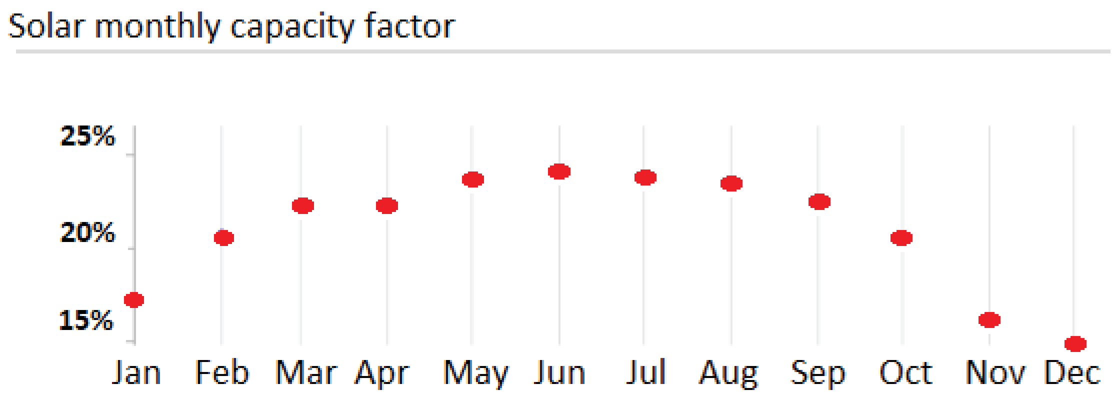

Figure 1. Monthly capacity factor for solar technology.

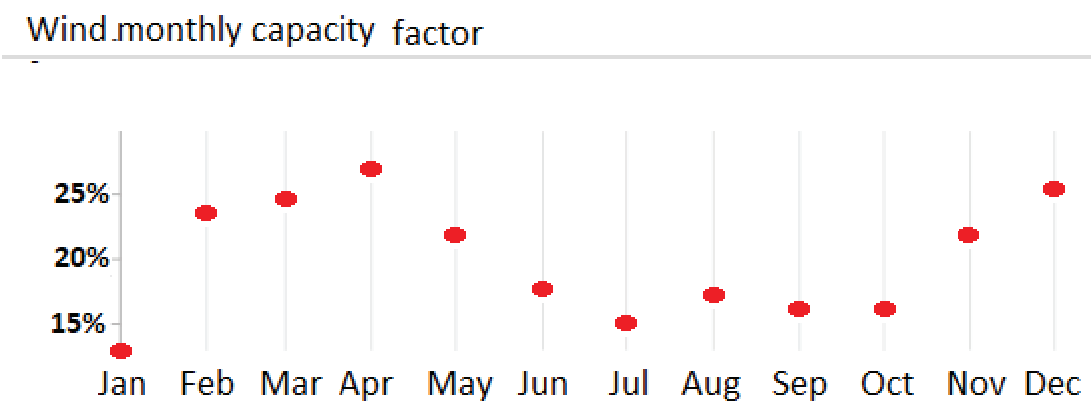

Figure 2. Monthly capacity factor for wind technology.

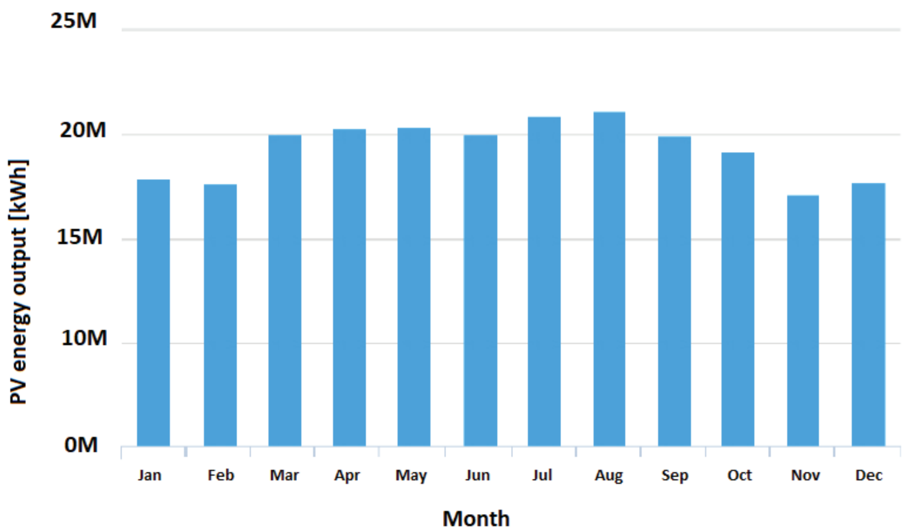

Figure 3. monthly energy produced by a solar plant.

The estimation of monthly and annual energy generated by a solar plant with a capacity of 100 MW was made by PVGis. The annual energy produced by the installation is equal to 172315438 kWh. The energy production of a wind turbine with the same capacity was calculated using RETScreen Expert software. The energy produced annually by this plant is 556819339 kWh, which is two times higher than the energy produced by the solar plant with the same capacity.

The following part of this section contains a detailed analysis of the levelized cost of energy.

Figure 4 shows a comparison between an adiabatic and a diabatic compressed air energy storage technology. The comparison shows the levelized cost of energy of the two CAES derivatives versus their lifetime. The results show a decrease in LCOS over the lifetime. It can be seen that the Levelized cost of storage of the diabatic system is higher than that of the adiabatic system. This difference can be explained by two reasons: the low efficiency of DCAES, which directly affects the energy yield of the system, and the dependence on fuel, which affects and increases the operation and maintenance costs of the system. Conversely, the adiabatic system's thermal energy storage system reduces the need for fuel combustion, thus increasing the overall efficiency of this system. The average costs of ACAES and DCAES are 0.0749 and 0.1108 \$/kWh, respectively.

Figure 5 shows the LCOE for wind and solar technologies. The evolution of the LCOE of solar and wind systems are similar. It can be seen that the LCOE of wind systems is lower than solar systems. The average values of LCOE of solar and wind systems are 0.1442 and 0.0579 \$/kWh,

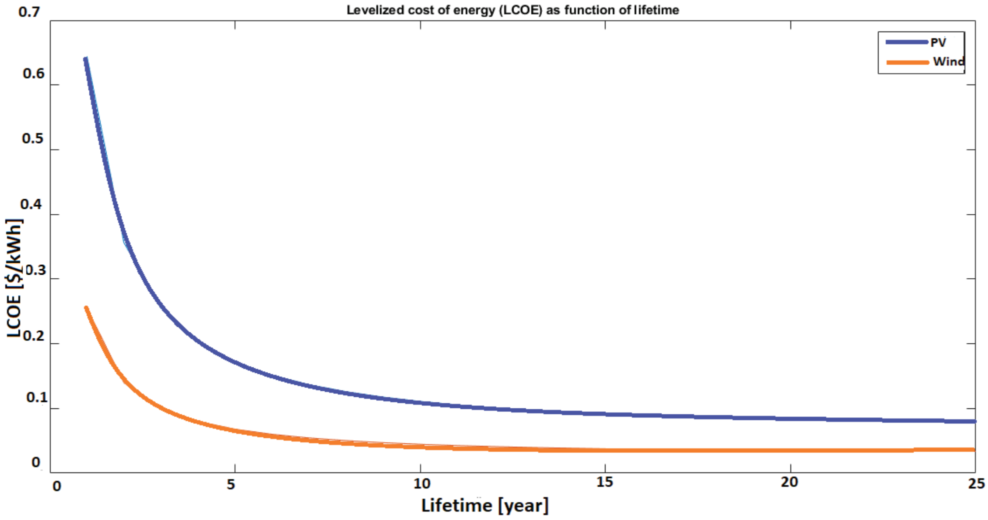

Figure 4. LCOS of compressed air energy storage.

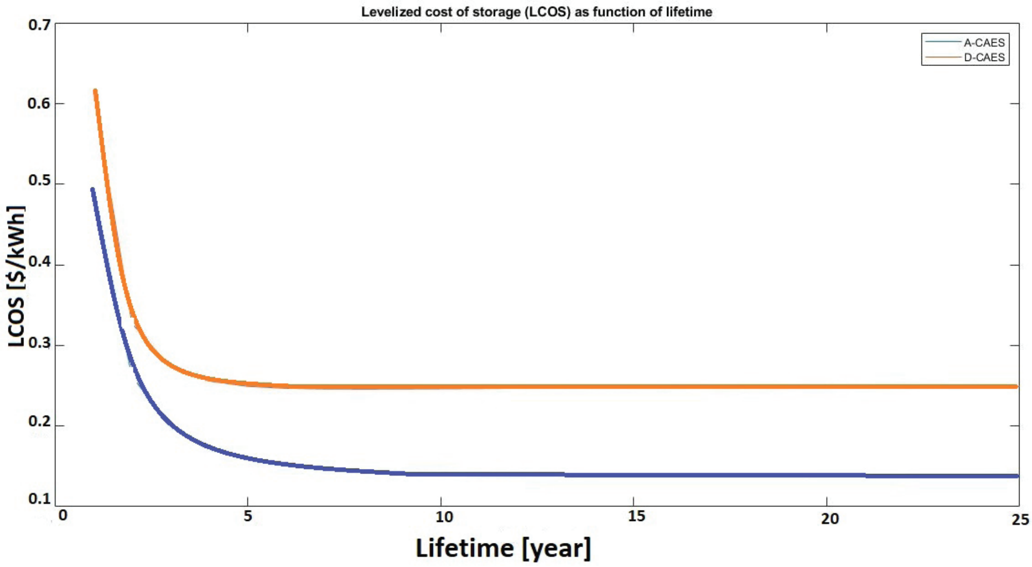

Figure 5. LCOE of wind and solar technologies.

respectively. Furthermore, the price of electricity generated by solar installation is three times that of wind installation, which is due to the high productivity of wind plants compared to solar plants in that area.

Figure 6 and Figure 7 show the evolution of the LCOES of the four possible combinations of solar or wind energy with ACAES and DCAES systems. The results confirm that the wind-ACAES combination is the most profitable. The average value of LCOES for the wind-ACAES combination is 0.11 $/kWh, while the average value for the solar-ACAES combination is 0.23 $/kWh.

In Figures 4, 5 and 6 the Levelized Cost of Electricity (LCOE), Levelized Cost of Storage (LCOS), and Levelized Cost of Energy and Storage (LCOES) are analyzed as function of different financial and economic parameters such as capital costs, operational costs, interest rates, and the expected lifetime of the system.

The electricity prices proposed by the National Office of Water and Electricity (ONEE) in Morocco are shown in Table 5.

Table 5. Medium voltage electricity prices in Morocco [28]

Period Electricity	prices [$/kWh]
Peak hours (7pm-11pm)	0.15
Flat hours (7am-7pm)	0.1
valley hours (11pm-7am)	0.076

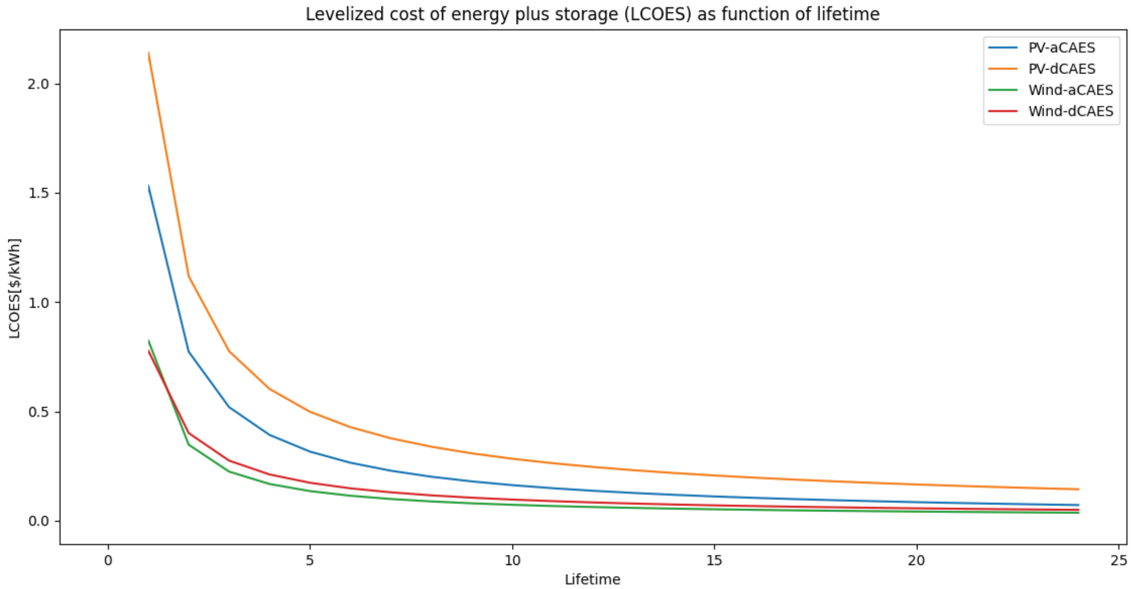

Figure 6. LCOES of the combination between Renewable energy and CAES system.

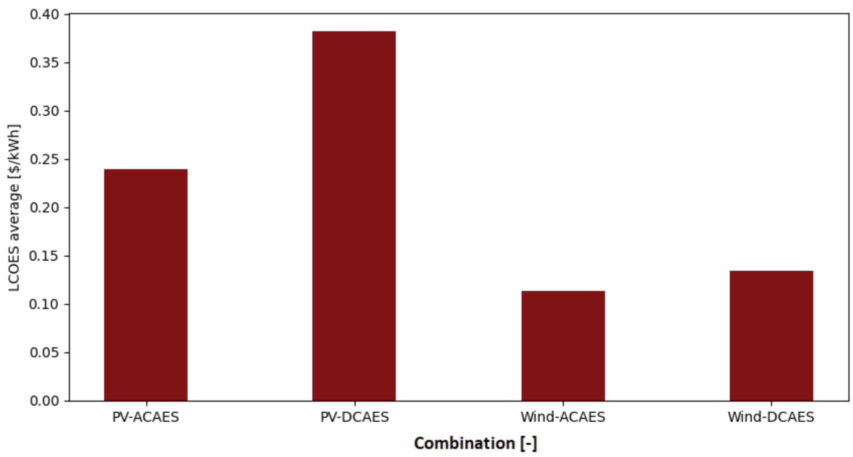

Figure 7. The average cost of energy for each combination.

Considering the price of medium voltage electricity in Morocco, the results obtained are very convincing. A wind turbine coupled with an adiabatic compressed air energy storage system offers optimum electricity prices, especially during peak hours when the electricity generated by the wind turbine is two times lower than the price proposed by ONEE. Moreover, the energy price of the combination is two times lower than the current price in the valley hours when energy demand is low. Therefore, this combination is the best way to get sustainable, green and cheap energy.

Arndt et al. [29] present the LCOE of different power generation plants (solar, coal, wind and nuclear) as a function of lifetime based on IEA data. The LCOEs of solar and wind power projects are very similar to those found in this paper. The LCOE of solar plants are three times higher than those of wind plants at the beginning and reach their lowest values after a few years of operation. Shields et al. [30] found a decrease in the LCOE of wind turbines by more than 40% within 5 years. The LCOE values continue to decrease and reach a stable value at the end of the project lifetime.

Hansen's [31] article conducts an analysis of two cost estimation approaches, namely the Levelized Cost of Energy (LCOE) and the Energy System Analysis (ESA) methods, with a focus on their comparison in the context of electricity, decentralized heating, and district heating technologies within two system configurations of the German energy system. The LCOE obtained in this work for PV installation ranges between 0.072and0.104 per kWh.

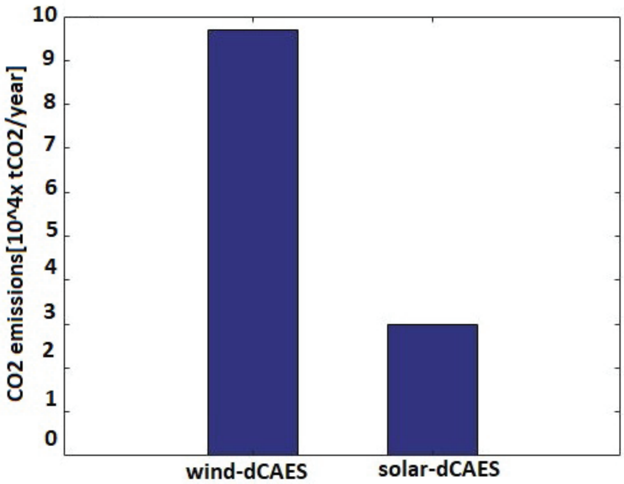

Figure 8. Yearly CO2 emissions by combination.

The environmental impacts of the solar-DCAES and wind-DCAES combinations are shown in Figure 8. It can be seen that the combination of wind and DCAES emits three times more CO2 than the combination of solar and DCAES. The fact that wind energy provides much more energy than solar energy in the Casablanca region means that the DCAES system requires more natural gas to reheat the compressed air stored in the salt cavern before injecting it into turbines. In the calculation, it is assumed that each MWh of energy stored emits 0.3865 tCO2 [RetScreen]. In the case of DCAES, the system is independent of fossil fuel use. Therefore, it is not necessary to study the environmental impact of this storage system.

Figure 7 presents the average values obtained from Figures 4, 5, and 6. These average values have been calculated for the purpose of comparing them to electricity prices. Figure 8 shows the amount of CO2 emissions for the two combined systems: the diabatic storage system in combination with solar and wind energy technologies.

CONCLUSION

The Moroccan government has decided to increase the share of renewable energy, especially solar and wind power, in the overall energy mix. This is intended to increase the share of electricity generated from renewable sources. The intermittent nature of renewable resources requires an additional storage system. In the current studies, compressed air storage has been considered as a promising storage technology. The results of our research are very convincing in technical and environmental terms, so the following conclusions can be drawn:

- Underground salt caverns and abandoned mines are crucial for large-scale energy storage and minimize the investment cost of the installation compared to aboveground storage, especially pressure vessels.
- The combination of wind and adiabatic compressed air energy storage results in the best levelized cost of energy and storage costs compared to other combinations.
- The Ain Tekki salt mine is a good option for large-scale storage of hydrogen, liquefied natural gas, and compressed air. Therefore, Morocco is a fertile land for this type of facilities.

NOMENCLATURE

$E_{w,s}$	Annual Energy generated by power plant, MWh /Year
$P_{w,s}$	Rated power plant MW
O&M	Operation and maintenance cost, $/kWh
CAPEX	Capital cost , $

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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