Citation: Mahmoud, M., Ramadan, M., Olabi, A-G., Pullen, K. R. & Naher, S. (2020). A review of mechanical energy storage systems combined with wind and solar applications. Energy Conversion and Management, 210, p. 112670. doi: 10.1016/j.enconman.2020.112670

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Link to published version: https://doi.org/10.1016/j.enconman.2020.112670

A Review of Mechanical Energy Storage Systems Combined with Wind and Solar Applications

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Abstract

Mechanical energy storage systems are among the most efficient and sustainable energy storage systems. There are three main types of mechanical energy storage systems; flywheel, pumped hydro and compressed air. This paper discusses the recent advances of mechanical energy storage systems coupled with wind and solar energies in terms of their utilization. It also discusses the advances and evolution in each type and compares them in terms of performance, capacity, response and utilizations. The reviewed studies exhibit all parameters that affect the performance of each storage type in which the configuration of the system has the major effective role. Choosing the suitable mechanical storage type depends on the requirements of each application such as using the flywheel for short duration applications. If long duration is needed, then it is preferred to use either pumped hydro or compressed air storage systems, knowing that the former has higher efficiency while the latter provides a faster start up. For the sake of the environment, it is recommended to use the adiabatic or isothermal compressed air storage. In all cases that combine MESSs with solar or wind energy, the series connection is preferred in order to provide stability and better control strategy.

Keywords: Energy storage, mechanical energy storage, renewable energy, solar energy, wind energy.

Nomenclature	
ACAES	adiabatic compressed air energy storage
BWES	buoyancy work energy storage
CAES	compressed air energy storage
CI-CAES	closed isothermal compressed air energy storage
CVaR	conditional value at risk
DRP	demand response program
DSTATCOM	distribution static synchronous compensator
ESS	energy storage system
FESS	flywheel energy storage system
HT	hydraulic turbine
HVDC	high voltage direct current
I-CAES	Isothermal compressed air energy storage
IM	induction machine
IWPS	isolated wind power system
LCOE	levelized cost of energy
MESS	mechanical energy storage system
NPV	net present value
OI-CAES	Open isothermal compressed air energy storage
PHES	pumped hydro energy storage
PV	photo-voltaic
SG	synchronous generator
SM	synchronous machine
SNG	synthetic natural gas
SP	stochastic programming
SRM	switched reluctance machine
SST	solid state transformer
TC	thermochemical
UGCAES	underground compressed air energy storage
UWCAES	underwater compressed air energy storage
VC-ACAES	variable configuration adiabatic air energy storage

WTG	wind turbine generator

1. Introduction

In the last few decades, energy consumption, particularly electricity usage are found to be significantly increasing due to rising world population and living standards. The fastest jump of energy consumption growth in this decade was recorded in 2018 as 2.13% [1]. Additional energy supplies must be provided in order to balance the increasing demand. The critical issue is which different sources and techniques can be adopted to cover this energy demand. Fossil fuels cannot be considered a solution for satisfying energy demands due to their critical negative effects on the environment and must be phased out [2]. Nuclear energy seems to be a solution because of its low CO_2 emissions, but it is too expensive and suffers from other drawbacks such as security risks. For this reason, there is need to rely on renewable sources and energy waste recovery systems to prevent the environmental damage from air pollution leading to global warming. Renewable energies offer the best approach for provision of energy due to their sustainable nature and broad utilizations because of their diverse presence such as wind, solar, geothermal, bioenergy and hydropower. On the other hand, renewable sources usually cannot standalone in a power plant because of their intermittent nature and significant fluctuations especially when considering wind and solar energies [3]. This fact imposes on the researchers to find an alternative solution or to perform efficient combinations; where they find that energy storage systems (ESSs) can solve the stated problem when coupled with the renewable energy resources [4].

Advantages of Energy Storage Systems

In addition to the ESSs main advantage which is to store the excess of energy, they offer many other benefits:

- Increasing renewable energy penetration and decreasing its curtailment because a power plant cannot depend only on a renewable energy source without an ESS. As a matter of fact, fuel consumption and CO_2 emissions will decrease [5].
- Balancing between the energy supply and demand while smoothing renewable energy fluctuations due to its intermittent nature [6]. This will also mitigate the problems in electrical systems of power generation.
- Shaving the peak energy loads which will indeed decrease the risk of load shedding especially when large capacity of storage is considered.
- Improving the overall efficiency of a power plant and consequently reducing the operating cost at the long run [7].
- The flexibility of ESSs provides the convenience and suitability to cover remote areas which generally suffer from lack of electricity [8].

1.1 Energy Storage Systems Classifications

ESS provides flexibility to the system in order to cope with the fluctuations and intermittent nature of renewable sources, it can also accommodate the energy demand fluctuations. In other words, ESSs mitigate the imbalance between the supply and demand. Storage systems can improve grid stability and system’s performance, increase penetration of renewable energy sources, and reduce fossil fuel energy resources utilizations and consequently their environmental impacts. Due to the multiple utilizations of energy and different types of applications, ESSs have always been undergoing development and different storage systems are established. ESSs are mainly classified into three main categories as presented in Figure 1 [9-11]. Table 1 presents the environmental impacts of some ESSs.

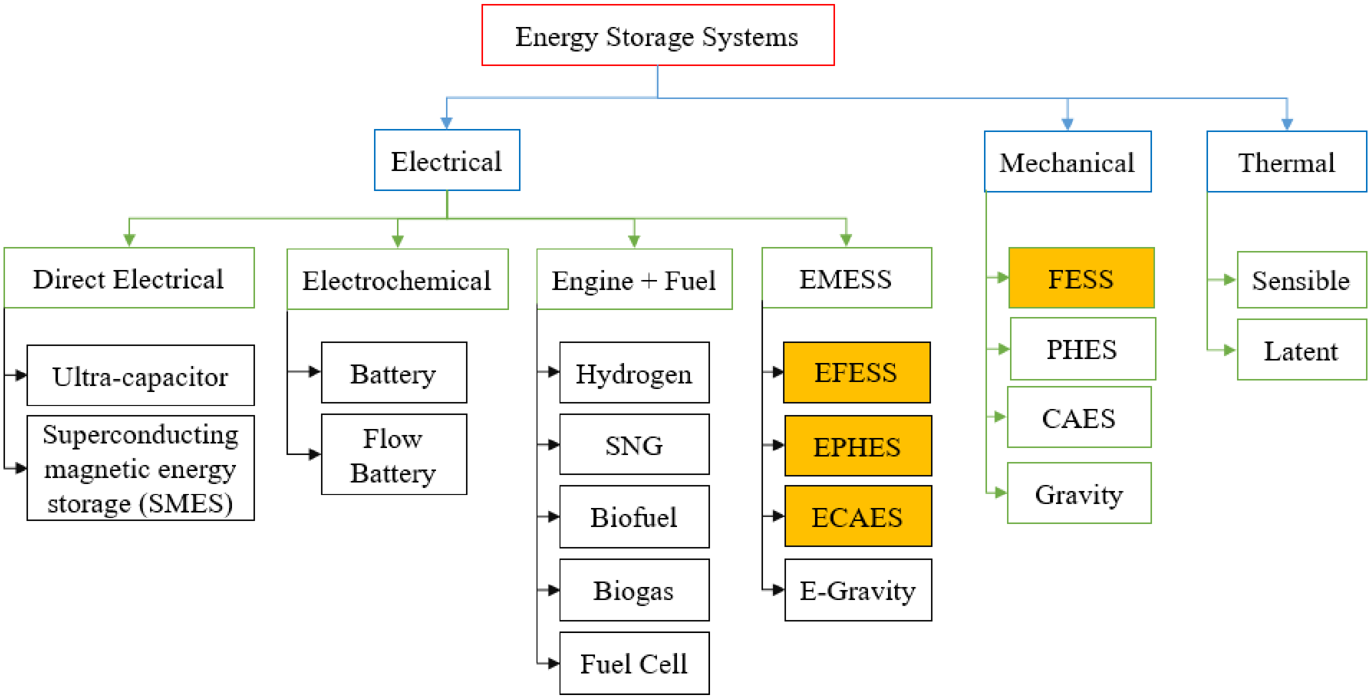


Figure 1: Energy storage systems Classifications; the orange marked types are the most commonly used mechanical energy storage systems

Mechanical energy storage systems can be found either as pure mechanical (MESS) or combined with electrical (EMESS). The main difference is in the utilization of stored energy if it is directly used or transmitted via an electric motor-generator. Usually EMESSs are used to supply the grid with electricity. On the other hand, MESSs are able to provide mechanical work such as smoothing the rotation of a rotating mass which is the case of flywheel. The orange marked types in Figure 1 are the most commonly used mechanical energy storage systems.

Table 1: Environmental impacts of the commonly used energy storage systems

Energy Storage System	**Environmental Impact**
Synthetic natural gas (SNG)	Haze pollution and greenhouse gases [12]
Biofuel	Biodiversity, water quantity and quality problems [13]
Biogas	Hazardous alkanes such as methane [14]
Thermochemical (TC)	Depends on the reactants and products
Batteries	Consumption of resources and heavy metal pollution [15]; ex: lithium ion degrades and not recyclable
Super capacitors	Carbonization [16]
Thermal	Depends on the material (ex: organic vapour is carcinogenic) [17]
Mechanical energy storage	Relatively low

1.2 Mechanical Energy Storage

Mechanical energy storage systems (MESSs) are highly attractive because they offer several advantages compared to other ESSs and especially in terms of environmental impact, cost and sustainability. There are three main types of MESSs, as shown in Figure 1; flywheel energy storage system (FESS) [18], pumped hydro energy storage (PHES) [19] and compressed air energy storage (CAES) [20]. MESSs can be found in some other different forms such as liquid-piston, gravity and mechanical springs. The crucial issue in choosing the appropriate system among these depending on the source of energy, load nature and available space. It is also necessary to mention that there are some common advantages between the different types of MESSs such as the relative fast response and nil environmental effects. These types of ESSs produce less contaminants in both operational and construction levels, which is indeed an important factor to improve air quality in order to avoid human health diseases.

The aim of this paper is to review all applications involving MESSs combined with solar and wind energies in order to present the parameters that affect the performance of each system. The characteristics of all systems will be discussed in addition to their advantages and disadvantages. A detailed comparison will be presented depending on the different storage systems and configurations. This will be accompanied by presenting the recent investigations on the different mechanical energy storage systems in addition to the development of each domain.

2. Flywheel Energy Storage System

Flywheel energy storage system (FESS) [21] is based on storing energy for the short-term by using a rotating mass in the form of kinetic energy [22] as shown in equation (1). In terms of fast response, flywheels are the most effective ESSs while taking the economical aspect into consideration [23]. There are different applications where FESS can be used: hybrid vehicle, railway, wind power system, marine and space [24]. One of most studied applications on FESS is the regeneration of braking power in locomotives, trains and cars [25]. These studies focused on storing the braking energy lost in order to give power again for acceleration. This aims to save energy [26], decrease the peak power [27], improve the efficiency, reduce emissions and fuel consumption [28]. Flywheels can be found in four different shapes; disc of Laval, solid disk, thick ring and thin ring (see Figure 2) [29]. Each flywheel is characterized by a shape factor (K) representing the utilization of material. The specific energy stored per unit of mass is proportional to K which is presented in equation (2). These equations show the effects of inertia, speed and shape on the energy stored by the flywheel.

$$E = \frac{1}{2} I w^2 \tag{1}$$

$$\frac{E}{m} = K \frac{\sigma_{max}}{\rho} \tag{2}$$

where E is the stored energy, I is the moment of inertia, w is the rotational speed, m is the mass, σ_{max} is the maximum stress and ρ is the density of the flywheel.

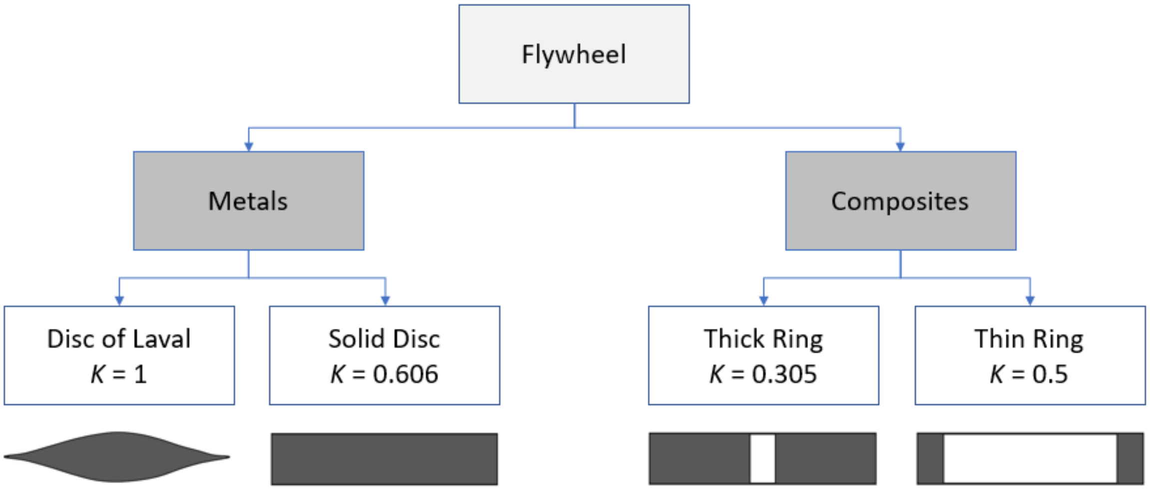


Figure 2: Different flywheel shapes, *K* is the shape factor

The main components of FESS are as shown in Figure 3; bearings, rotating mass, motor-generator and a frequency inverter. The overall efficiency depends on the design of each component, and one of the main objectives is the reduction of power transmission losses which is affected by the type of bearing; it was found that magnetic bearings are the best choice [30]. There are also three different types of electric machines that could be coupled to the FESS; synchronous machine (SM), induction machine (IM) and switched reluctance machine (SRM). SRM is the less commonly used type due to the high current ripples and control complexity. Usually, SM and IM are used for high speed and high-power applications respectively. In terms of performance, SM is better than IM because it has lower inrush at the start [31]. Beside the usage of flywheel for energy storage, it is used to increase the life time of batteries [32] when coupled with renewable sources due the intermittency nature.

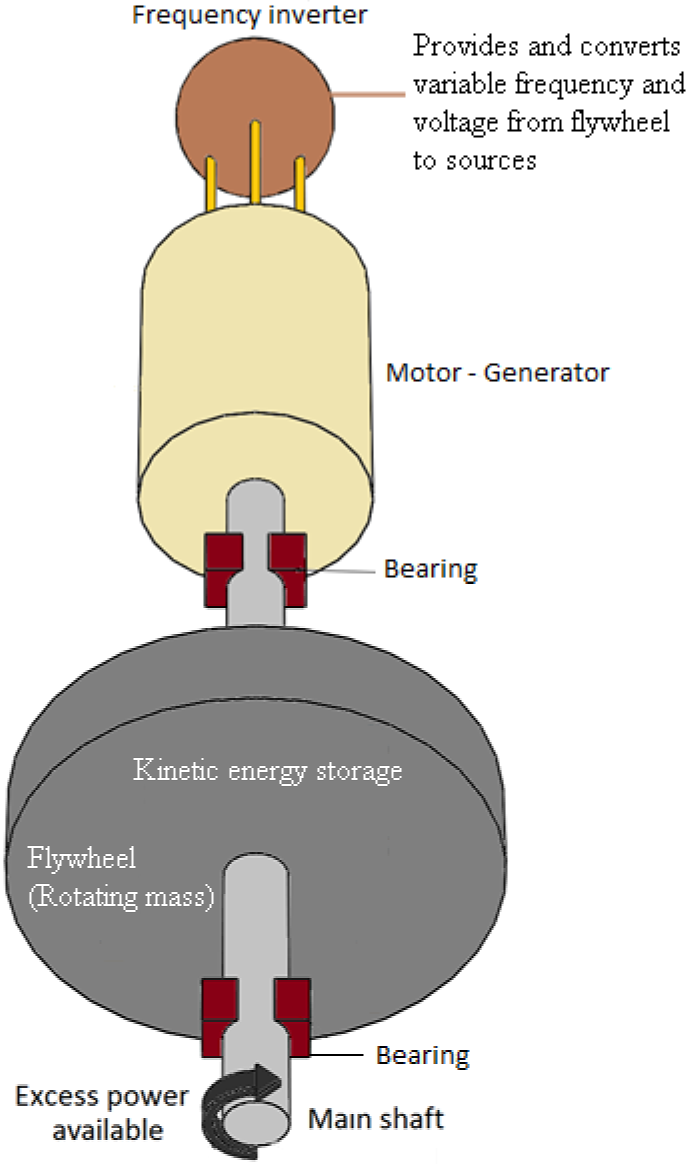


Figure 3: The main components of the FESS

2.1 Wind Energy Coupled with Flywheel Storage

Wind-FESS is a system that is taking lot of interest nowadays. Wind energy is one of the most favorable sources used for generating electricity, while there is always a common problem faced which is the mismatching between supply and demand. This is due to the variations in both wind and available load which can cause problems in the network. This requires a fast response energy storage which makes the use of FESS more favorable. This ESS can be used to smooth the wind power [33] and to supply energy to the users with different demands for achieving better power quality [34]. The coupling between wind and FESS is also known as isolated wind power system (IWPS) [29] which is usually formed from a wind turbine generator (WTG), consumer load, SM and a flywheel. FESS is almost used in medium to high power (kW to MW) applications for short-time periods (seconds/minutes). Gadelrab et al. [35] introduced FESS to enhance the wind farms-fed high voltage direct current (HVDC) transmission system via a two-stage solid state transformer (SST). Several control strategies [36] were investigated to reserve and smooth wind turbine power by using FESS, and the proposed methods were found to be applicable for all wind speeds. One of the most effective control strategies is the classical squirrel-cage induction machine using cascade rectifier filter inverter [37] which was modeled and simulated in order to overcome the stochastic nature of wind. Electric system problems are in fact one of the major problems in the Wind-FESS. Suvire and Mercado [38] found that mitigating these electric problems can be performed by using a Distribution Static Synchronous Compensator (DSTATCOM). This compensator maintains the active power approximately constant and equals to the average power that would be produced otherwise.

A comparative study was simulated in [39] between a variable and constant speed flywheels in order to study the effect of hydrostatic transmission (see Figure 4). The authors deduced that this kind of transmission between the flywheel and the synchronous generator (SG) can decrease the frequency deviation and energy losses. Mansour et al. [40] investigated the variable speed wind generator to find the optimal methods for regulation. Two controllers were examined; the proportional integral and the fuzzy controller. It is concluded that the permanent magnet synchronous generator can offer the suitable regulation path to smooth the power flowing to the grid.

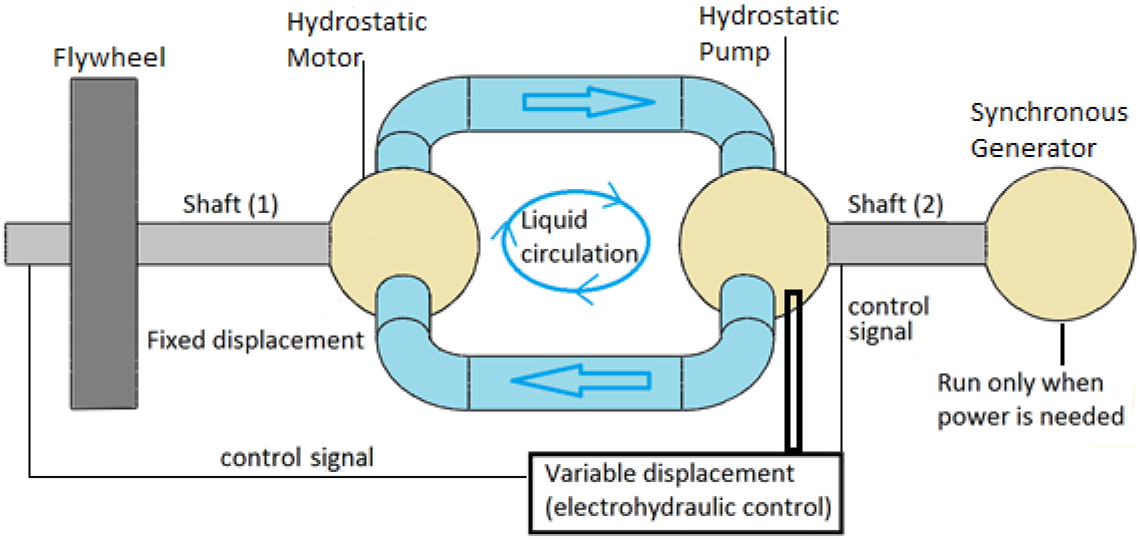


Figure 4: FESS with hydrostatic transmission

3. Pumped Hydro Energy Storage

Pumped hydro energy storage (PHES) is a MESS which is characterized by its long-life cycle, flexibility and low maintenance cost. It is formed of three major components; pumping system, hydro turbine (HT) and upper reservoir [41]. Figure 5 shows an example of the PHES. Water is pumped from the lower reservoir to the upper one when there is an excess of energy, so it can be used again when needed. This system depends on the potential gravitational energy such that the upper container is able to provide positive pressure difference with respect to the lower one and consequently to produce power by the help of the HT. Advanced PHES relies on replacing the turbomachines by a reversible pump-turbine in order to enhance the performance of the storage system and response time as well as increasing its flexibility [42].

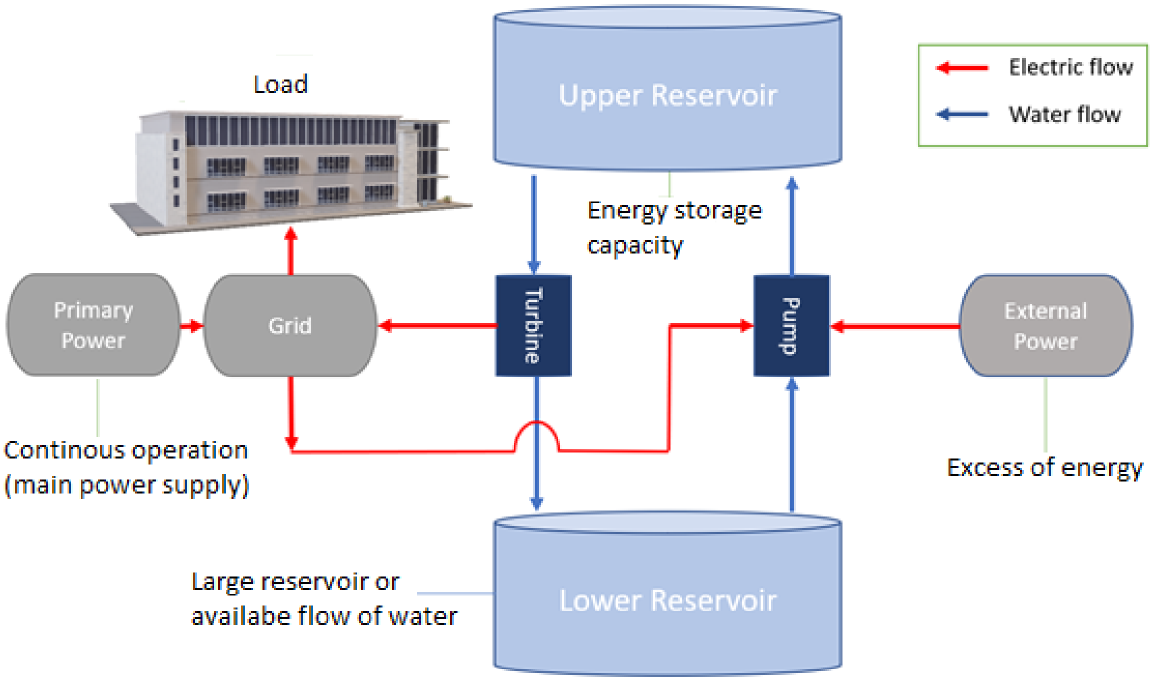
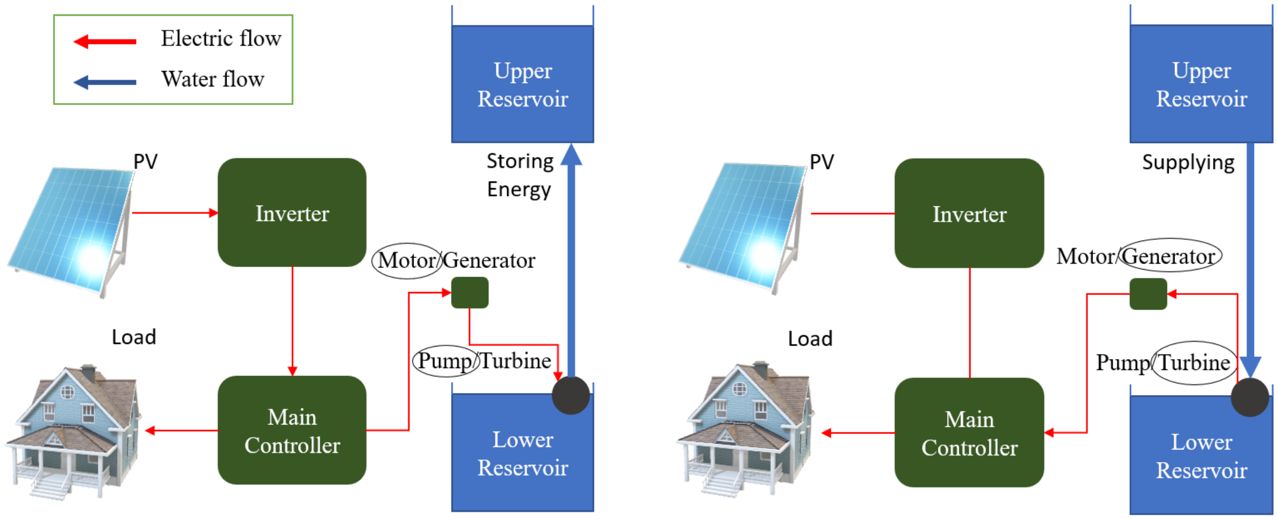


Figure 5: The flow of energy in the PHES plant

3.1 Solar Energy Coupled with Pumped Hydro Storage

Solar-PHES is an efficient strategy for mitigating the photo-voltaic (PV) power fluctuations. It is necessary to support this system with an accurate forecasting of Solar-PHES power generation and demand response, followed by a smart grid energy management [43] for achieving the optimal operation. In [44], Solar-PHES was used to minimize grid power cost for irrigation in the presence of boreholes for water supply. Figure 6 represents the working process of the system during 24 hours (day and night). The day configuration shows how the solar energy is able to store water in the upper reservoir by using the pump. At night, in the absence of sunlight, the water will flow back to the lower reservoir passing through the motor-generator which is connected to the control center responsible for supplying power.



(a) (b)

Figure 6: Solar coupled with PHES (a) storing and (b) supplying power

Usually the optimization of Solar-PHES is used to decrease the overall operating cost of PHES and that of the PV. This system has been adopted to operate in remote areas or islands without any grid supply in order to decrease the levelized cost of energy (LCOE) and increase power supply reliability [45]. As presented in Figure 6, the solar PV is able to either generate electricity directly or pump the water to the upper reservoir. Bahadur et al. [46] suggested that the solar power must only be used to pump water. By this way, the system will be simpler and no need for control systems because it is automatically controlled. The PHES will remain receiving power from the wind turbine and supplying the grid via the hydraulic turbine. In [47], floating PV was integrated with PHES in order to avoid the need for reserving specific land sources and to provide the required amount of water.

3.2 Wind Energy Coupled with Pumped Hydro Storage

Wind-PHES is a combination usually used in islands where interconnection grids can be found in which wind energy represents the main energy source. It aims to increase renewable energy penetration [48] as well as to decrease the LCOE [49], total power shortage [50] and the amount of energy produced by conventional power plants [51]. In a Wind-PHES system, the wind turbine is directly connected to the pump which is responsible for driving the water for the upper tank. In order to estimate the economic and environmental impacts of the Wind-PHES, it is necessary to study the main uncertainties that are wind speed and electricity load. The mixed-integer nonlinear programming is a stochastic programming that allows to investigate the effect of these uncertainties appropriately [52].

PHES could be used to smooth the offshore wind power variations [53], balance between power supply and demand [54], decrease the imbalance cost [55] and wind power uncertainties. It also provokes a decrease in the start-up effect of peaking units [56] and the risk of load shedding [57]. The wind turbine could be connected mechanically to the pump via gearbox or electrically by transferring the wind power to electric energy. Both types have special characteristics, however, the electrical form is more commonly known and used. This is due to the high-power loss and fluctuations that may occur mechanically. Kapsali et al. [58] found that the HT is better to operate 24 hrs, and the upper reservoir volume should be designed in a way to provide the HT the whole operational time (day-night). Al Zohbi et al. [59] investigated a new method to store the surplus of wind energy in dams, and compared between two dams in Lebanon (Chabrouh and Quaraoun) in order to choose the best one. In [60], an optimization study was carried out aiming to use Wind-PHES for desalination and minimizing wind power curtailment [61], and consequently to decrease the power cost, water production cost and CO_2 emissions (see Figure 7). In a conventional Wind-PHES system, part of the excess power released by the wind turbine is released and the rest is curtailed. Therefore, it will be very helpful to use this curtailed power for desalination. This could fit the Wind-PHES extremely knowing that water is a major component in the storage and desalination systems. As a matter of fact, the need for fossil fuels will decrease in water production systems.

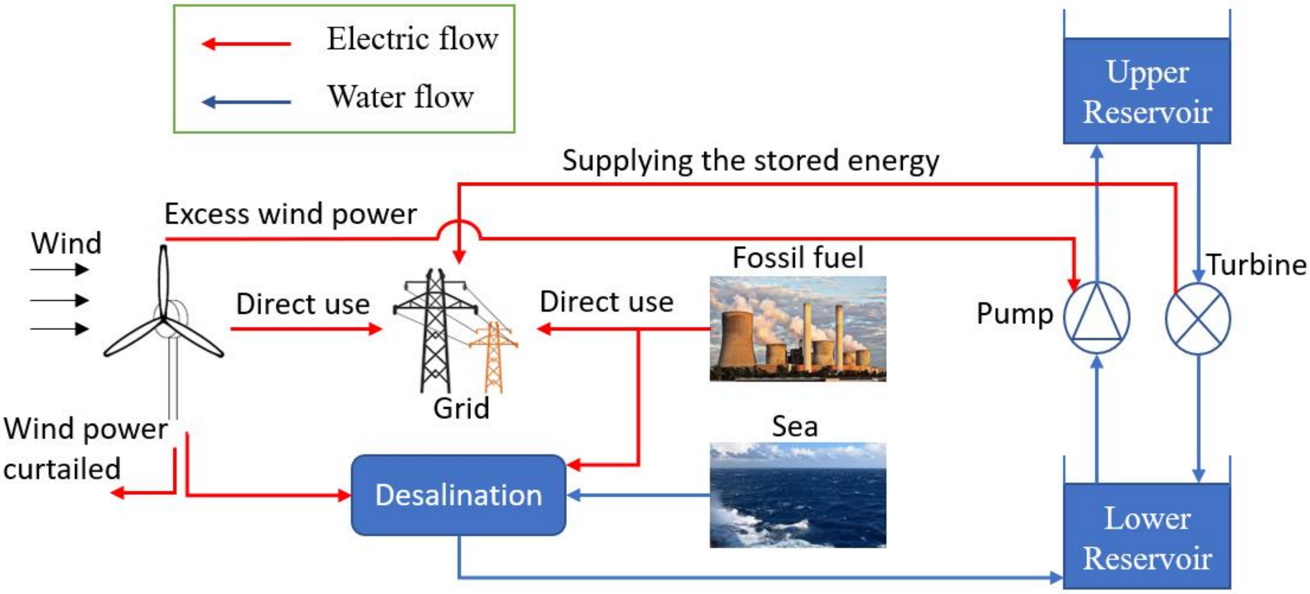


Figure 7: The principle of desalination based on wind energy coupled with PHES

The optimization of the system is not only considered at the design level and components' sizing [62], but it also depends on optimal operations and scheduling [63] such as the initial stored water [64] in the upper reservoir which is better to be as high as possible. One of the drawbacks of Wind-PHES is its high capital cost [65], thus, Foley et al. [66] encouraged the use of this system while making it commercially viable by decreasing its capital cost and penalizing fossil fuel with high carbon taxes. Intelligent energy management can be performed in agricultural micro grids to benefit from the Wind-PHES and support irrigation systems [67]. Another way to make the system economically feasible is to increase the penetration of wind [68]. This will raise the profit of PHES and thus its payback period. With this in mind, it is necessary to always recheck if the system is working on its optimal operation, because each operation must be specific for a limited amount of power. Canales et al. [69] compared between Wind-PHES and the conventional reservoir. The authors deduced that Wind-PHES is much better even though it has a higher initial cost but it has lower operating cost, environmental impact and flooded area [70]. The capital cost of the system depends highly on the wind energy availability and plant construction area [71]. In [72], variable speed pumps were investigated to provide fast dynamic response that was also found to be a profitable solution [73]. Endegnanew et al. [74] discussed three different types of controllers that could be used in the Wind-PHES; storm, HVDC and load following controller. In [75], it was found that using double penstock instead of one will decrease the wind energy rejected annually from 18.96 % to 4.67 %. Bahadur et al. [76] proposed an optimal way to smooth the wind power by connecting the wind turbine in series with PHES. In other words, the wind turbine is not connected to the generator directly. The water in the upper reservoir is always responsible for generating electricity.

4. Compressed Air Energy Storage

Compressed air energy storage (CAES) is based on storing the excess of energy underground in the form of compressed air (see Figure 8). The compressed air will be subjected to heat addition before it enters the expander for generating electricity. Part of the compressed air will pass through a natural gas turbine that produce electricity and the rest will be used for heating the compressed air flow before expansion. CAES is an eco-friendly ESS which does not require high maintenance. There are different types of underground air storage; porous rock, mired hard rock storage facility and leached out salt dome. Underground air storage is only used for large scale applications, because it will not be effectively operating otherwise. Thus, for small scales, it is recommended to use aboveground storage formed of wire wound pressure vessels [77]. Amir et al. [78] aimed to increase the feasibility of RES and CAES. It was deduced that the proposed system has the ability to provide combined heat and power. This will indeed raise the benefit of this system and decrease its payback period to become less than 3 years. This could be achieved by replacing the combustion chamber with a thermal storage tank in order to take advantage of the stored heat. The latest generation of CAES is the isothermal version (I-CAES). It uses water to compress and expand the stored air via pump/turbine. This allows a reduction in the electric consumption of the compressor, elimination of the need for thermal input completely and an increase the overall efficiency of the storage system. It depends on two different mediums; air as a storage medium and water for controlling the pressure of the stored air. This system could be found as open (OI-CAES) or closed system (CI-CAES). The closed type is the conventional one such that it consists of only one storage tank combining air and water. However, the OI-CAES uses two working cylinders connected to each other with a reversible valve in order to increase the energy storage density which is expected to be double than that of CI-CAES [79].

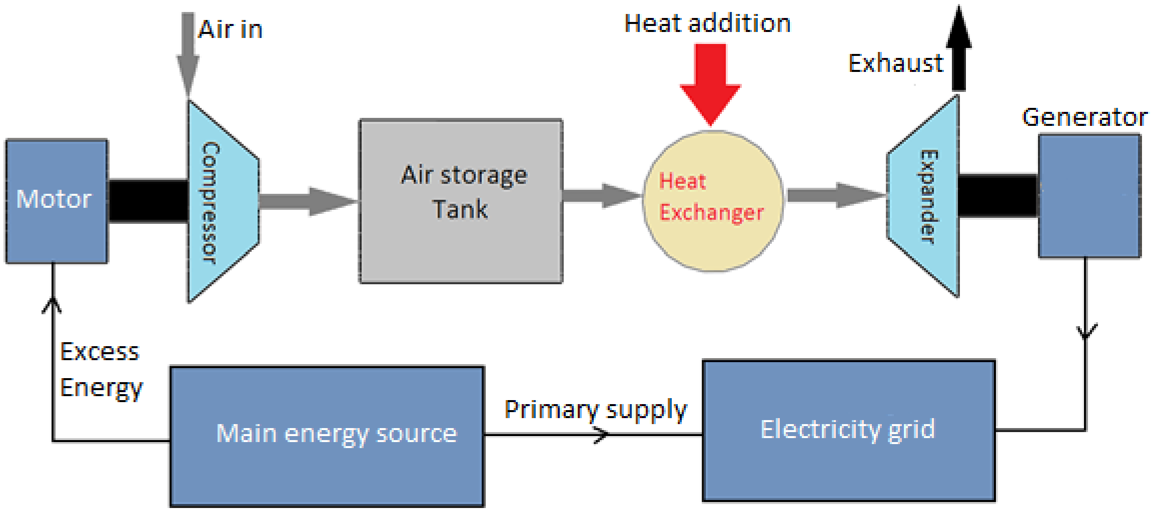


Figure 8: Schematic diagram of a conventional CAES

4.1 Solar Energy Coupled with Compressed Air Storage

Same as the previous mentioned ESSs, Solar-CAES aims to decrease fuel consumption and CO_2 emissions. In Brazil [80], the annual average exergy and energy efficiencies of the plant was measured to be 17.9 % and 16.2 % respectively. According to [81], Solar-CAES has been investigated as an effective system in a PV farm under transient operational conditions, which consequently enhances the stability of the output power of the PV-plant and increases the net revenue. In [82], CAES sizing was performed in a PV-farm case study to provide electricity where the ESS is used to increase the efficiency of the PV-plant. Cazzaniga et al. [83] established a new integration between CAES and floating PV-plant. The pontoons of the floating PV are used as reservoirs, and steel cylinders instead of polyethylene pipes. This system can be implemented in water basins in which the buoyancy of the modular raft structure must be pre-studied.

4.2 Wind Energy Coupled with Compressed Air Storage

In these days, Wind-CAES is frequently used for energy storage in offshore wind energy farms which is environmentally friendly [84]. Indeed, using such coupling, the power can be shifted to peak hours for increasing the gross revenue [85]. On the other hand, electrical stability of the system can be achieved by an optimal scheduling [86] and by taking into consideration the load distribution and peak times [87]. Jin et al. [88] investigated a small-scale Wind-CAES with a wind turbine rated power of 2 MW. The storage capacity used was 1.32 MWH. It was noticed that the proposed system is able to stabilize the output power while having a CAES rated power of 0.44 MW. In a case studied in Egypt [89], the net present value (NPV) was increased from \$207m to \$306m by using the CAES compared to the stand alone wind turbine after 25 years of operation. According to [90], Wind-CAES has CO_2 emissions 93% lower than the pulverized coal and 71% than the natural gas cycle. Abbaspour et al. [91] compared between Wind-CAES and the gas-fired generation plant, in which the results showed that the Wind-CAES could increase the profit by 43% and decrease the costs by 6.7%. Abdul Hai Alami [92] compared between CAES and Buoyancy work energy storage (BWES) in wind farm and find that the efficiency of CAES (84.8 %) is much higher than that of the BWES (36 %). In [93], a thermo-economic study was performed in which the authors mentioned that CAES is a cost-effective solution for solving local wind power grid imbalances.

Table 2: Difference between Wind-CAES, Wind-NGCC and Conventional Coal Systems

Systems	Carbon Dioxide Emissions ($g\ CO_2/kWh$)	Fuel Consumption (MJ/kWh)
Wind-CAES	61	1.03
Wind-NGCC	216	4.22
Conventional Coal	876	9.71

Usually optimization studies [94] are performed in Wind-CAES to support the main objectives of the system such as decreasing the LCOE [95] while increasing the CAES capacity and rated power requirements for the compressor. This can be achieved by an optimal utilization of wind power and operation profitability [96] that vary according to the schedule of wind generation [97]. The main components affected by the change of wind speed are the wind turbine and compressor; in which the highest efficiency could be achieved at stable and medium wind speeds [98]. In [99], it was concluded that a variable shaft speed could serve in decreasing the LCOE when compared with that of the constant speed. Saadat et al. [100] modelled a dual chamber liquid-compressed air storage vessel (hydraulics and pneumatics) in order to downsize the electrical system, increase profit and match between grid and load. Hasan et al. [101] concluded that a parallel CAES system combined with wind turbine is better than the series connection which consumes less amount of power during compression and also can deal more with wind fluctuations. Figure 9 shows the difference between the series and parallel connections of the Wind-CAES. Wang et al. [102] compared between the Underwater CAES (UWCAES) [103] and Underground CAES (UGCAES). The authors found that UWCAES has a higher efficiency in an offshore wind farm application. In [104], UWCAES was also studied, it was reported that the total operating cost of the system is decreased by 3.36%. Underwater storage is provided by the help of two vessels; one is seabed and connected to the second which is responsible for floating the wind turbine. The system will stay balanced and floating by the support of the lower pressure vessel. The compressed air is also used to feed the grid when needed. In this floating offshore spar type wind turbine [105], a hydraulic pump based on liquid-piston is used to compress the air while providing low compression ratios to reduce losses and hence increasing the overall efficiency.

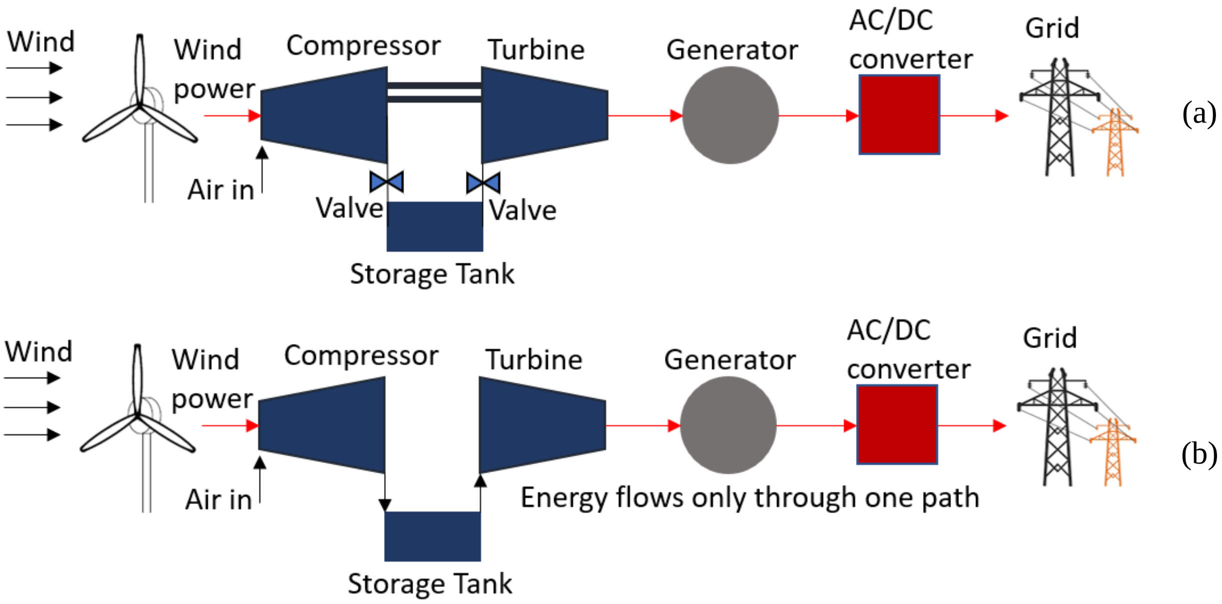


Figure 9: Wind coupled with CAES (a) Parallel and (b) Series connections

Adiabatic CAES (ACAES) [106-108] is a modern type of ESS which is introduced to many wind power applications to eliminate heat addition in order to get rid of gas turbines [109] (see Figure 10). It is a gas free system; the released thermal energy during compression is stored to be then reused before expansion. Therefore, the ACAES is mainly dependent on the thermal energy storage used [110]. Zhang et al. [111] proposed a variable configuration of the ACAES (VC-ACAES) to reduce power fluctuations using multi-stage compressor and multi-stage expander to operate under variable modes and to increase the wind power connected to the grid from 26.29 % to 70.62 %. According to the economic aspect, the centralized CAES in wind power applications is found to be a better choice than the decentralized one [112]. Sun et al. [113] modelled mathematically the scroll expander to be used as an air-machinery energy converter in order to transmit additional driving power from the stored compressed-air to the turbine shaft for smoothing the wind power. The co-location of wind and CAES is found to be attractive to decrease the transmission costs and to increase the wind penetration.

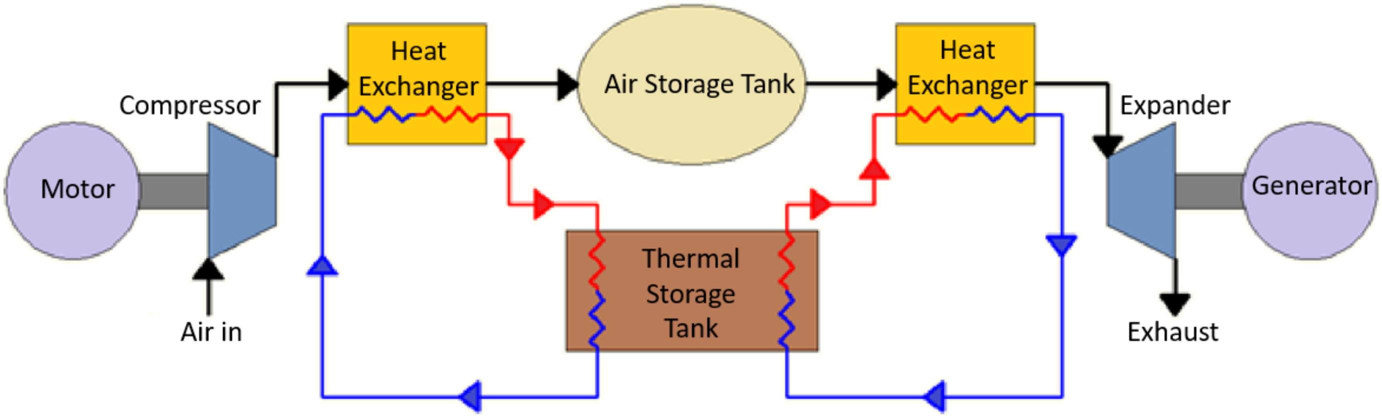


Figure 10: ACAES schematic representation

In the presence of demand congestion, it is essential to adopt programs for management issues and operational strategies [114] in order to deal with scheduling problems. Currently, the most important programs used are the demand response program (DRP) [115] and stochastic programming (SP) [116]. These are used as feedback methods to get rid from intermittency, decrease the operational cost, reduce wind curtailment and provide better frequency security [117]. One of the main studies that must be carried out using these programs is the conditional value at risk (CVaR) [118].

5. Mechanical Energy Storage Coupled to Hybrid Systems

Hybrid systems are used to increase the utilizations of renewable energy as well as to combine the advantages of the different types of MESSs. They also allow to decrease the negative effects of fuel power cycles and to combine between different sources of energy. Table 3 shows the different combinations of MESSs and energy sources. The combinations can be found in two different ways; either by energy sources or by ESSs. Typical hybridizations of energy sources can be the Solar-Wind, Solar-Diesel, Wind-Diesel, etc., while that of ESS can be such as FESS-CAES, CAES-Thermal ESS, etc. One of the main benefits of using hybrid systems is to adopt standalone renewable energy systems. This could be achieved by coupling an energy storage system to wind and solar energy. Therefore, in [119], the ACAES was chosen as a storage system in order to avoid any other thermal input. The results showed that the probability of losing the power supply is very low such that it will not exceed 1%. The capital cost is the main concern when talking about hybrid systems, however, if the operating cost is significantly reduced, then the capital cost issue could be skipped. These systems are mostly adopted in remote areas where the grid has not been extended. For instance, Solar-Wind-PHES [120] can decrease the levelized cost of electricity by 32.8% and 45% compared to Solar-PHES and Wind-PHES respectively [121].

Table 3: Hybrid systems based on mechanical energy storage

Hybrid System	References
Solar-Diesel-FESS	[122]
Solar-Diesel-PHES-Batteries	[123]
Solar-Gas Turbine-CAES	[124]
Solar-Organic Rankine Cycle-CAES	[125, 126]
Solar-Wind-CAES	[127, 128]
Solar-Wind-FESS	[129]
Solar-Wind-PHES	[130-135]
Wind-Diesel-CAES	[136]
Wind-Diesel-FESS	[137, 138]
Wind-Diesel-PHES	[139]
Wind-Electric Boiler-PHES	[140]
Wind-FESS-CAES	[141]
Wind-Gas Turbine-PHES	[142]
Wind-Geothermal-CAES	[143]
Wind-Organic Rankine Cycle-CAES	[144, 145]
Wind-Thermal Unit-PHES	[146]
Wind-CAES-Thermal ESS	[147]

6. Discussion

The current increase in the usage of renewable energy imposes also to increase in MESSs in order to obtain the needed performance. The evolution and development of MESSs start to show up after 2010 as shown in Figure 11 based on the papers analyzed in this research. It is clearly observed that during the last four years, the number of articles of MESSs combined with solar and/or wind is in a dramatic growth which shows the importance of this topic nowadays. The results presented in the figures of this section are based on Elsevier journals as a sample study.

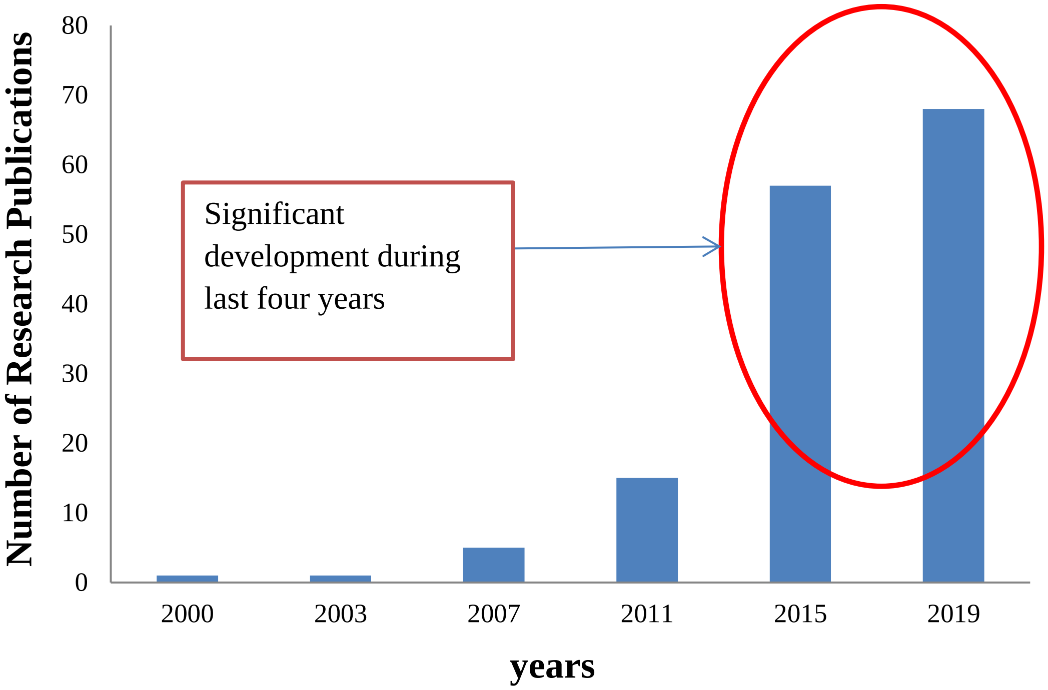


Figure 11: The research development of MESSs coupled with solar and wind applications

Comparison between mechanical energy storage systems

Indeed, the evolution of MESSs domain varies significantly with respect to its different types according to global requirements which depend on the properties and advantages of each type. Figure 12 presents the difference between the MESSs types combined with solar and/or wind energy applications regarding the number of studies and research publications. This difference is directly affected by the performance of each type, storage capacity, operating duration, initial and operating cost and environmental effects.

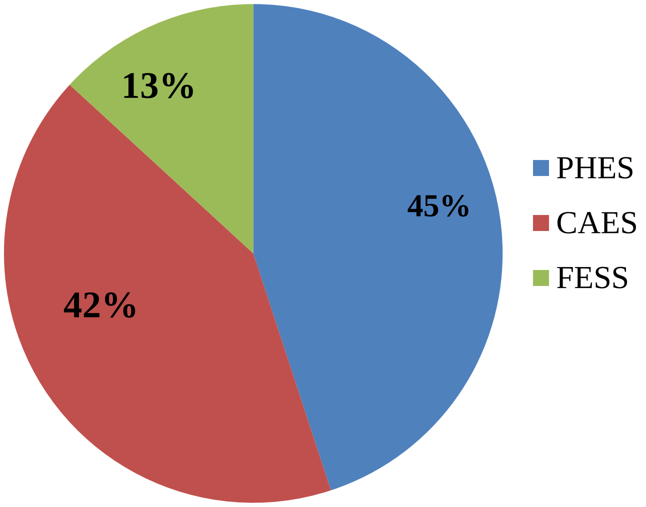


Figure 12: The difference between mechanical energy storage systems when coupled with wind and solar energies according to the number of studies and articles

The nature of the energy source is a major factor that affects the MESS type selection. As a matter of fact, the characteristics of wind energy is more appropriate than solar to be coupled with MESSs. This is due to the type of component responsible for energy conversion in each system. Therefore, the mechanical power generated by the wind turbine could be easily transmitted to any type of MESSs. Figure 13 shows the difference between wind and solar energies according to the type of mechanical storage systems. It is very noticeable that wind is considerably more investigated than solar energy when coupled with all mentioned storage systems. The percentages of Wind-PHES and Solar-

PHES applications are 78% and 22% while that of Wind-CAES and Solar-PHES are 85% and 15% respectively. FESS is only coupled with wind energy (100%) because this storage system could only be used to store mechanical power.

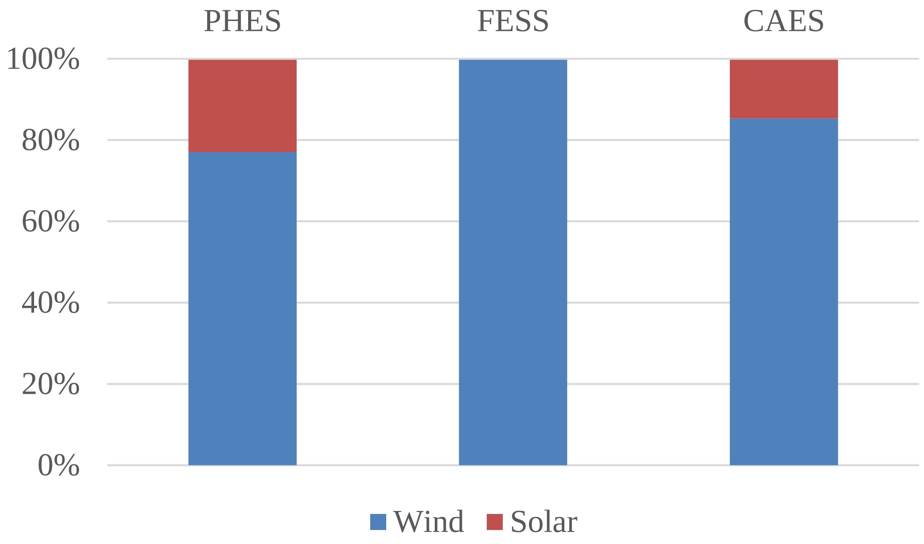


Figure 13: The percentage difference between solar and wind energies with respect to their combinations with mechanical energy storage systems

As shown in Figure 14, the applications involving wind/solar and MESS had passed through several jumps and drops. Recently, the highest investigated application is the Wind-CAES. It has been remarkably increasing; however, the other systems are either decreasing or remaining constant. Besides, the curves corresponding to solar energy are always below those of wind. This confirms that wind energy is more applicable with mechanical energy storage.

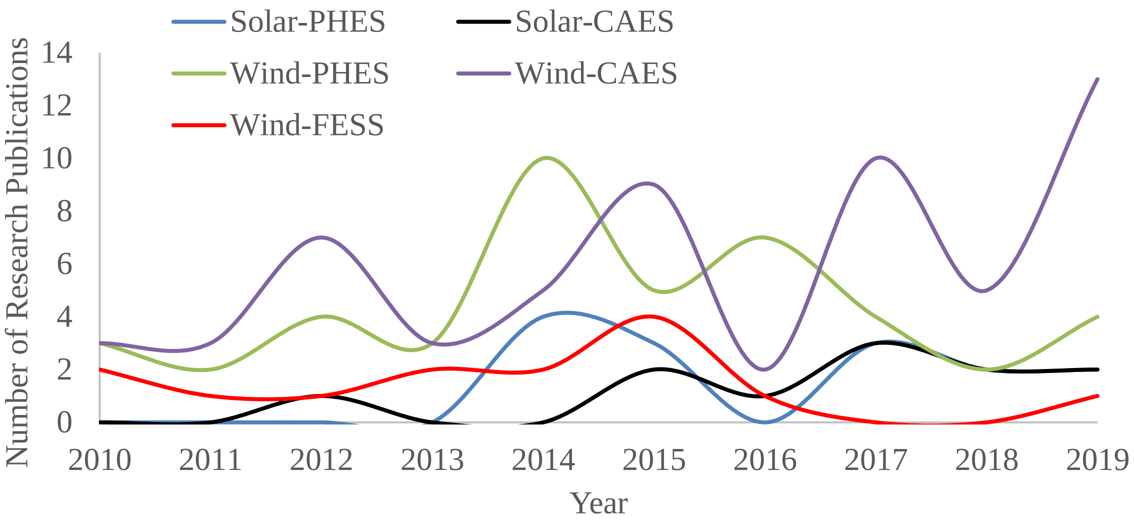


Figure 14: The number of researches that investigated the different applications combining wind/solar energy with MESSs with respect to time

It is essential to study the difference between the various types of energy storage in order to choose the appropriate system to feed the needs in the case or application under study. There are also some special characteristics and differences between the different types of MESSs such as the very rapid discharging of power in FESS, high efficiency of PHES regardless of time and the stability of CAES. Table 4 shows a comparison between the different types of MESSs involving the advantages and disadvantages of each one.

Table 4: Comparison between the types of MESSs

ESS	**Advantages**	**Disadvantages**
FESS	• No pollution • Long lifetime • Discharging huge amount of power in few minutes	• Limited charge/discharge • Cannot stand alone with a PV plant

	• Low cost/kW	
PHES	• High efficiency • Stability • Low cost/kWh • Long discharge time	• High capital cost • Low energy density • Occupying large areas • High capital cost
CAES	• Flexibility • Long discharge time • Fast start-up • Low cost/kWh • Stability	• Low efficiency • Usually natural gas is used to reheat the air before expansion leading to CO_2 emissions (if not using ACAES/I-CAES)

Recommendations

Due to the fundamental difference in terms of operational mode and characteristics, recommendations for using MESSs are very specific and adapted to the considered storage type. A pre-study should be performed relying on the geographic and economic conditions of the region in order to select the optimal type of MESSs. Since PHES requires a large amount of water, so it is not preferred to use this kind of energy storage in areas that have low available amount of water. This system could also take advantage of net power from rain in mountains. With this in mind, the temperature is also considered as a critical factor such that it must be moderate to avoid freezing and evaporation at low and high temperatures respectively. Moreover, it is suggested to adopt such system in places characterized by huge differences in elevations because it allows to increase the effectiveness of PHES. To increase the profit of this system, a variable speed pump must be installed [72]. The series connection between the wind/solar power with PHES is able to provide more stability [46, 76]. This is a kind of automatic control to avoid complexity since the HT will remain operating which is the only component connected to the generator. FESS is the most economic ESS when fast responses are required within a short operational time [23]. Magnetic bearings are responsible for decreasing the transmission losses [30]. The less commonly used electric machine is the SRM because it has complex control problems. Usually, SM and IM are used for high speed and high-power applications respectively [31]. It is very necessary to use compensators such as DSTATCOM to stabilize the output power in FESS when coupled with renewable energy [38]. Furthermore, hydrostatic transmission and SG could serve in decreasing frequency deviations [39]. It is recommended to replace conventional CAES by modern types such as ACAES [109] and I-CAES [79] in order to avoid using another heat source which will consequently increase the plant efficiency and reduce the CO_2 emissions. VC-ACAES [111] has showed a great potential for decreasing the power fluctuations which relies on multi-stage compressor and multi-stage turbine. Floating wind/solar [83, 105] systems coupled with CAES are also highly attractive because they are depending on underwater storage which has presented a better performance compared to the underground one [102]. In all MESSs, it is very necessary to adopt well organized operational strategies and feedback programs such as DRP [115] and SP [116]. The governmental sector should support projects involving MESSs. This can be performed by providing the information needed for the studies as well as the lands required for the plants' construction.

Research gaps and future directions

- Development of software that allows to choose the optimal energy storage system based on the available conditions, power supply and load. This will indeed help the users to select the most suitable storage system that could fit their applications.
- Study advanced hybrid MESSs to improve the plant efficiency and get rid of the disadvantages of the different types of storage systems as much as possible. It will be easier to shave peak loads and increase the capacity of the whole plant. Hybrid MESSs is the optimal way to keep the system eco-friendly and meet the requirements needed in any type of application.
- Perform modeling and preliminary studies on hybrid systems combining MESSs with other ESSs. This will help in studying the potential of these hybrid systems in order to find further optimization options. Even though, combining MESSs alone is the favorable choice of energy storage, however, in some special cases, they are not capable of meeting all requirements. Thus, coupling different energy storage categories is necessary, while, the most important issue is their management such that the MESSs are the primary systems and others are the auxiliary ones to reduce the environmental impact as much as possible.

7. Conclusion

This review paper has investigated all research studies involving wind and/or solar applications coupled with MESSs. These types of RESs are the most ones that require energy storage such that they are characterized by significant intermittency. This domain has showed a dramatic development and evolution recently. The coupling could be found in two different ways; series and parallel. It was deduced that series connection is preferable such that it provides an automatic control in order to reduce the sudden drop or rise in solar or wind power. By this manner, power will be enforced to flow first through the MESS then to the load. This will ensure stability and safety of the devices that are connected to the system and simplify controlling issues. On the other hand, the parallel connection could save more amount of power such that the path of energy flow is shorter than that of series. The three main categories of mechanical energy storage systems are FESS, PHES and CAES. FESS is based on storing energy for short durations in the form of kinetic energy by using a rotating mass. Indeed, it has the fastest response where it can discharge huge amount of power in few minutes however its capacity is very limited. It is the most economic ESS in terms of fast response (lowest cost/kW). There are two electric machines that are commonly used in flywheels; SM for high speed and IM for high power applications. In order to stabilize the electric power, it is essential to use a compensator such as DSTATCOM. In the presence of significant fluctuations, hydrostatic transmission and SG would be the most favorable solutions. PHES depends on storing water in an elevated reservoir, it can then be used as a stored potential energy. PHESs are optimal for regions where large spaces are available as well as sufficient amount of water. It has the highest efficiency, but it requires larger areas for installation.

Variable speed pumps are better than that of constant speed in terms of profit. The HT will stay operating the whole time providing the grid with the needed power. CAES, in its turn, relies on using a compressor to store air at high pressure, it can be then expanded when it is required in order to supply energy. It is very flexible and has a fast start-up while it operates at lower efficiencies compared to other MESSs. Therefore, using ACAES instead of the conventional CAES allows to avoid the need of a supplementary heat source by the help of a thermal storage tank. It is also more favorable to use VC-ACAES to decrease power fluctuations and/or floating systems that are based on underwater storage to provide higher storage efficiencies compared to that of underground. The high-power consumption of the compressor could also be reduced by using the I-CAES because it is based on compressing air with a pump by the help of water as a working fluid. In addition, OI-CAES has a higher energy storage density compared to the closed type.

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