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Wind-Diesel hybrid system: energy storage system selection method

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1. Introduction

Canada is an immense country and while most of the population is concentrated near the US border, there is more than 300 000 peoples living in isolated communities that are not connected to the electrical grid [1]. In those remote places, electricity is produced using diesel generators at very high economic and environmental costs. Since most of these locations possess good wind conditions an obvious solution to reduce this burden is to couple a wind turbine with the diesel generator. However, in the absence of a storage system, the penetration factor must be kept low due to the constraints related to the operation of the diesel generator. This leads to a waste of the wind turbine electricity and significantly reduces the economic interest of the method. Penetration factor can be largely increased by the addition of an energy storage system. The utilization of the excess energy allows a much more stable power and the complete stop of the diesel generators when they are not needed and a close to optimal performance of it, which reduces their maintenance cost. Nevertheless, the optimization of the whole system is critical to reach an adequate level of performance. This paper describes this optimization process and the selected system concept.

2. Overview of wind-diesel hybrid system

A wind-diesel hybrid system is any autonomous electricity generating system using wind turbine(s) with diesel generator(s) to obtain a maximum contribution by the intermittent wind resource to the total power produced, while providing continuous high quality electric power [2]. Figure 1 presents a schematic diagram of a generalized wind-diesel system.

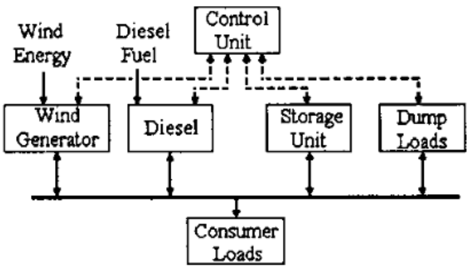

Figure 1. Schematic of generalized wind-diesel system [3]

The main goal with these systems is to reduce fuel consumption and in this way to reduce system operating costs and environmental impacts. These fuel consumption savings are maximum with wind-diesel systems with high wind penetration, in which the diesel(s) generators may be shut down during high wind availability. A system is considered to be a high penetration system when the amount of wind produced at any time versus the total amount of energy produced is over 100%. If the system is in the way that diesels have to run full time, the wind-diesel hybrid is classified as low or medium wind penetration depending on the ratio wind power output/primary electrical load [3]. Low penetration systems are those with less than 50% peak instantaneous penetration and medium penetration systems have between 50%-100% of their energy being produced from wind at any one time. Low and medium penetration systems are a mature technology. High penetration systems (> 100% peak instantaneous penetration), however, still have many problems, especially when installed with that capacity to operate in a diesel-off mode.

3. Problems related to wind-diesel hybrid system

Hybrid wind-diesel systems with high penetration of wind power have three plant modes: diesel only (DO), wind-diesel (WD) and wind only (WO). In DO mode, the maximum power from the wind turbine generator (WTG) is always significantly less than the system load. It is the mode of classical diesel power plant. In this case, the diesel generators (DG) never stop operation and supply the active and reactive power demanded by the consumer load. Frequency regulation is performed by load sharing and speed governors controlling each diesel engine and voltage regulation is performed by the synchronous voltage regulators in each generator. The main goals of maximize fuel savings or minimize generation costs to supply the actual load [5] is achieved by careful planning/scheduling of the DG having into account factors such as their specific fuel consumption, their rated power, etc.

Wind-Diesel mode can be considered as a diesel plant with the wind turbine as a negative load. It is the mode of many low/medium wind penetration power wind-diesel systems already implemented in Nordic communities in Yukon [6], Nunavut [7] and in Alaska [8]. In this case, the WTG power is frequently approximately the same as the consumer load and in addition to DG(s), WTG(s) also supply active power. Some new problems appear in this mode like to determine the diesel spinning reserve (the wind power can disappear in any moment due to the unpredictable wind resource and the current load can overload the diesel(s) currently supplying), or to assure a minimum diesel load needed by some engines (this situation can happen at high wind power levels and low loads). Under these conditions, two operating modes are possible: (1) the diesel can be allowed to run continuously, or (2) the diesel can be stopped and started, depending on the instantaneous power from the wind and the requirements of the load. Running the diesel continuously decreases the load factor, with an increase in the aforementioned diesel operating costs. Using the energy storage unit showed in Fig. 1 can solve both problems. The second problem can be solved by the use of the dump load showed in Fig. 1 or reducing the power coming from the wind turbine. Some variable speed wind turbines have this possibility [9]. Also in this mode additional reactive power must be generated, because wind turbines are normally reactive power consumers, although adding capacitor banks or overexciting the synchronous generators can solve this. However, the first obstacle with this perspective results from the operation constraints of diesels. Beyond a certain penetration, the obligation to maintain idle the diesel at any time, generally around 25-30 % of its nominal output power, forces the system to function at a very inefficient regime. Also, this limits the wind energy to a level of too weak penetration and the wind turbines act only as a negative charge for the network. Indeed, for low and medium penetration systems, the diesel consumes, even without load, approximately 50% of the fuel at nominal power output. These systems are easier to implant but their economic and environmental benefits are marginal [10].

The use of high penetration systems allows the stop of the thermal groups, ideally as soon as the wind power equals the instantaneous charge, to maximize the fuel savings. This is the wind only mode. The WO mode is only possible if the power coming from the wind turbine(s) is greater than the consumed power by the load (with a safety margin). Because no diesel generators run in this mode, auxiliary components are required to regulate voltage and frequency. The frequency is controlled through the active power balance. To accomplish this active power balance, the energy storage system can be added to store the surplus active power from the wind turbine or retrieve power in the periods when the wind power is less than current load; also the surplus wind power can be consumed by dump loads. The voltage is controlled by the reactive power balance and it is normally achieved through synchronous condensers which deliver the reactive power needed by the loads and the wind turbine. To supply power uninterruptedly, the size of the energy storage has to be big enough to assure power to the load during transitions from the wind power source to the diesel power source when there is a failure or absence of wind energy. In the meantime, the high-penetration wind diesel systems without storage (WDHPWS) is subject to complex technical problems [11], [12] which did that a single project of this type, without any storage, is presently operational in Alaska [8].

During time intervals when the excess of wind energy over the charge is considerable the diesel engine must still be maintained on standby so that it can quickly respond to a wind speed reduction (reduce the time of starting up and consequent heating of the engine). This is an important source of over consumption because the engine could turn during hours without supplying any useful energy.

Assuming optimum exploitation conditions [13], the use of energy storage with wind-diesel systems can lead to better economic and environmental results , allows reduction of the overall cost of energy supply and increase the wind energy penetration rate (i.e., the proportion of wind energy as the total energy consumption on an annual basis) [14].

Presently, the excess wind energy is stored either as thermal potential (hot water), an inefficient way to store electricity as it cannot be transformed back in electricity when needed or in batteries which are expensive, difficult to recycle, a source of pollution (lead-acid) and limited in power and lifecycle. The fuel cells propose a viable alternative but due to their technical complexity, their prohibitive price and their weak efficiency, their appreciation in the market is still in an early phase. The required storage system should be easily adaptable to the hybrid system, available in real time and offer smooth power fluctuations. It is therefore necessary to analyze the fundamental characteristics (technical and economic) of storage systems in order to establish comparison criteria and select the best technology for the high penetration wind-diesel hybrid system.

A detailed study based on a critical analysis of all the characteristics of the possible energy storage technologies; it was proposed a solution that meets all the technical and financial requirements while ensuring a reliable electricity supply of these sites. It is the wind-diesel hybrid system with compressed air energy storage (WDCAHS). This study demonstrates the value of compressed air storage for a high penetration wind-diesel hybrid system and its advantages with regard to the other energy storage technologies. It was based on the aggregation in a «performance index» of technical, economic and environmental characteristics of various storage methods. The validation of the choice of compressed air energy storage and the methodology used to calculate the performance index and to synthesis the obtained results will be discussed in the following sections.

4. Energy storage systems

The fundamental idea of the energy storage is to transfer the excess of power (energy) produced by the power plant during the weak load periods to the peak periods. Initially, electricity must be transformed into another form of storable energy (chemical, mechanical, electrical, or potential energy) and to be transformed back when needed. The stored energy should be quickly converted on demand and used in a wide variety of electric applications and load sizes. There exist different Energy Storage Systems (ESS) technologies; some of them are well studied and developed, while others are just emerging and waiting for new hardware technologies to make them cost-effective.

5. Classification of energy storage systems

There are many possible techniques for energy storage, using practically all forms of energy: mechanical, electrical, potential, chemical, and thermal. These have all been explored, leading to the birth of the techniques that will be cited herein. The storage technologies that answer to specific technical and economic criteria, which vary considerably as a function of the applications and needs, will obviously be of different types. The technologies are many, but a comparative study is rendered difficult by the fact that, among others, their levels of development vary greatly [15]. According to their applications, the storage systems can be divided into four categories [16]:

1). *Low-power application* in isolated areas, essentially to feed transducers and emergency terminals;
2). *Medium-power application* in isolated areas (individual electrical systems, town supply);
3). *Network connection application* with peak leveling;
4). *Power-quality control applications.*

The first two categories are for small-scale systems (case of remote areas) where the energy could be stored as kinetic energy (flywheel), chemical energy, compressed air, hydrogen (fuel cells), or in supercapacitors or superconductors. Categories three and four are for large-scale systems where the energy could be stored as gravitational energy (hydraulic systems), thermal energy (sensible, latent), chemical energy (accumulators, flow batteries), or compressed air.

6. Characteristics of energy storage techniques

Energy storage techniques can be classified according to these criteria [16]:

1) *The type of application*: permanent or portable;
2) *Storage duration:* short or long term;
3) *Type of production:* maximum power needed.

It is therefore necessary to analyze the fundamental characteristics (technical and economic) of storage systems in order to establish comparison criteria and select the best technology. The main characteristics of storage systems on which the selection criteria are based are the following:

6.1. Storage capacity

This is the quantity of available energy in the storage system after charging. Discharge is often incomplete. For this reason, it is defined on the basis of total energy stored which is superior to that actually retrieved (operational).

6.2. Available power

This parameter determines the constitution and size of the motor-generator in the stored energy conversion chain. It is generally expressed as an average value, as well as a peak value often used to represent maximum power of charge or discharge.

6.3. Depth of discharge or power transmission rate

The power output, or discharge, can be a limiting factor called the power transmission rate. This delivery rate determines the time needed to extract the stored energy. The power must be available for delivery during peak hours, that is to say the amount of energy used, if significant, is representative of a non-optimum system design, or a fundamental limit of the storage apparatus [18].

6.4. Efficiency

This is the ratio between released energy and stored energy. This definition is often oversimplified because it is based on a single operation point [19]. The definition of efficiency must therefore be based on one or more realistic cycles for a specific application. Instantaneous power is a defining factor of efficiency.

6.5. Discharge time

This is the maximum-power discharge duration. It depends on the depth of discharge and operational conditions of the system, constant power or not.

6.6. Durability (cycling capacity)

This refers to the number of times the storage unit can release the energy level it was designed for after each recharge, expressed as the maximum number of cycles N (one cycle corresponds to one charge and one discharge) [20].

6.7. Costs

Like any other investment, a storage system is an interesting venture when total gains exceed total expenses. The capital invested and operational costs (maintenance, energy lost during cycling, aging) are the most important factors to consider for the entire life of the system. Low-efficiency systems with low cycling capacity generally require the lowest initial investment. It is therefore crucial to carry out an analysis of the estimated durability of the entire system, including the storage unit [21].

6.8. Autonomy

This refers to the maximum amount of time the system can continuously release energy. It is defined by the ratio between the energy capacity (restorable energy) and maximum discharge power. The autonomy of a system depends on the type of storage and the type of application.

6.9. Self-discharge

This is the portion of the energy that was initially stored and which has dissipated over a given amount of non-use time [22].

6.10. Feasability and adaptation to the generating source

To be highly efficient, a storage system needs to be closely adapted to the type of application (low to mid power in isolated areas, network connection, etc.) and to the type of production (permanent, portable, renewable, etc.) it is meant to support (Figure 2). It needs to be harmonized with the network.

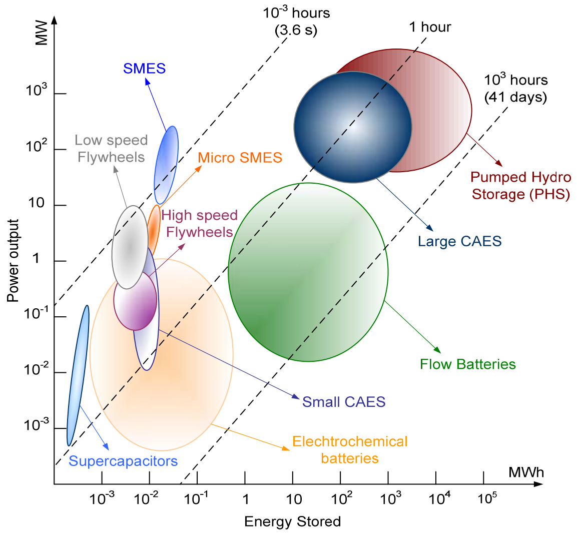

Figure 2. Fields of application of the different storage techniques according to energy needs [23]

6.11. Mass and volume densities of energy

These represent the maximum amounts of energy accumulated per unit of mass or volume of the storage unit, and demonstrate the importance of mass and volume for certain applications (especially for mass density of energy in portable applications, but less so for permanent applications).

6.12. Operational constraints

Especially related to safety (explosions, waste, bursting of a flywheel, etc.) or other operational conditions (temperature, pressure, etc.), they can influence the choice of a storage technology as a function of energy needs [24].

6.13. Reliability

Storage system reliability is always an important factor because it is a guarantee of on-demand service.

6.14. Monitoring and control equipement

This equipment, on both the quality and safety of storage levels, has repercussions on the accessibility and availability of the stored energy.

6.15. Environmental aspect

While this parameter is not a criterion of storage-system capacity, the environmental aspect of the product (recyclable materials) is a strong sales pitch. For example, in Nordic countries (Sweden, Norway), a definite margin of the population prefers to pay more for energy than to continue polluting the country [25].

6.16. Other characteristics

The ease of maintenance, simple design, operational flexibility (this is an important characteristic for the utility), fast response time for the release of stored energy, etc. [24].

7. Synthesis of the various energy storage techniques

To compare storage systems, Ragone's diagram is generally used to represent performance in terms of the ratio of mass to energy and power [26]. This type of conventional comparison is particularly interesting for portable units, for which mass is a critical aspect, but for permanent units, in a context of electrical-energy processing, life expectancy and total costs (investment, energy losses, and cycling fatigue) are the most important criteria [27]. Thus, these comparisons, overly simplistic, do not reach a definitive conclusion about the validity of the choice of compressed air to associate with a wind-diesel hybrid system. For this reason, a thorough and detailed summary will be presented in the next sections explain the selection of compressed air while based on techno-economic criteria listed above.

7.1. Electrochemical batteries energy storage (BES):

The lead batteries are the most economical investment at the delivery time of the system. Unfortunately, these batteries are susceptible to misuse and have various disadvantages which need to conduct further research, especially to improve their life cycling (charging and discharging). It is in the best case, about of a thousand cycles (approximately 3 years), which is very insufficient in production systems whose lifetime is about 15 to 20 years. Moreover, the "sudden death" of lead batteries in end of life is hardly compatible with the requirements of reliable power in remote locations.

Alkaline batteries (Ni/Cd and Ni/MH) are much more efficient, robust but more costly. They are better adapted to low temperatures and used where high reliability is required. By cons, the Ni/Cd suffers, according to the method of use, from a "memory effect" which reduces the usable capacity. Technically, lithium batteries have the best performance. Indeed, self-discharge of Li/ion is low and their stored energy density is much higher. They also allow a cycling at high deep of discharge with less impact on performance compared to the nickel/cadmium and lead batteries especially. Primarily for cost reasons, these batteries are still quite uncommon.

Finally, when the batteries are not recycled, they are a major source of pollution. For all these reasons, the batteries will not be adopted for wind-diesel hybrid system (WDHS).

7.2. Hydrogen energy storage (HES):

It is impossible to use hydrogen produced from wind energy as a fuel for diesel engines because they are not equipped with ignition systems. By cons, the use of the stored hydrogen to produce the electricity from a fuel cell designed to operate in the absence of wind and replace diesel for certain periods, seems a good alternative. But the poor performance of the overall electrolyser-fuel cell (35-40%), their unreliability, the prohibitive cost of capital and operating of this set and the safety aspect related to hydrogen storage, make sure they delay the acceptance of this technology by the market. For these reasons, the hydrogen storage will not be adopted for the WDHS.

7.3. Flywheel energy storage (FES):

This technology is not feasible to store large amounts of energy at long term. By cons, in the case of the supply of isolated sites, the flywheels can be used to store energy when production exceeds demand and improve the power quality where wind generation is close to the consumer level. Moreover, for a WDHS, the presence of an intermediary flywheel (by coupling the flywheel to diesel shaft) allows to reduce significantly the number of daily starts of diesel and increase the autonomy and the quality of the supplied current. Despite all these advantages, this technology has been excluded because it is a storage device for short time (a few tens of seconds to minutes) and requires, otherwise, massive materials to store energy, which increases the cost of system and of the used equipment. Moreover, this storage system will not allow a remarkable reduction in fuel consumption when the diesel functions in stand-by mode (periods of medium wind power penetration). Particular, may be added the issue of security related to the possibility of the collapse of the steering wheel.

7.4. Thermal energy storage (TES):

This type of storage, regardless of the technology used, can serve, using wind energy or excess heat from exhaust gases of diesel to produce hot water for heating or for use in the community where the WDHS exists. This system does not lead to reduce fuel consumption and GHG emissions. However, a better design may be offered and consists to couple the thermal energy storage (TES) to the wind-diesel-compressed air hybrid system. The TES will be used, in this case, as heat exchanger-storage device to recover the available heat in the air at the end of its compression and restore it afterwards during expansion of compressed air in the diesel engine or in an air motor. In conclusion, the TS will not be adopted as the main storage device associated with the WDHS but rather as an auxiliary system that improves the energy performance of the overall system.

7.5. Pumped hydraulic energy storage (PHS):

It is a large-scale storage and features a centralized production. So if it is available for remote sites, it will not be necessary to consider the use of diesel generators, especially if the wind potential is also available. By cons, storing small hydro requires abundant water resource in order to produce electricity; most of the criterion of geographical features is always present. For all these reasons, this technology has been excluded from the list of candidate technologies to be associated with the WDHS.

7.6. Redox batteries Energy storage (RBES):

Although the flow batteries can be used for small scale applications such as large scale, they are less mature and have yet to demonstrate their operation by hybridization with wind energy. Moreover, their prohibitive cost penalizes their integration into the market not to mention their contribution to the stopping of diesel is related to their autonomy, which also is depended to the reservoir volume of electrolytes in circulation and to the number of used cells (need large volumes and a high number of units). This increases the investment cost as well as the operating system. All these reasons exclude the possibility of adopting the flow batteries for WDHS.

7.7. Supercapacitors energy storage (SCES):

This type of storage is intended for small scale applications and its use at medium scale (case of WDHS) requires a series connection of several elements to achieve the required voltage. This will require more planning, more space and therefore more investment especially as the unit cost is quite high. The high self-discharge (5% per day), decreases the autonomy of the storage device and require a rapid consumption of wind energy stored before it is completely self-discharged without any use. This may slightly influence on the fuel consumption of diesel and its operating cost and make the overall system poorly operational and poorly harmonised. Consequently, this storage system will not be adopted for the WDHS.

7.8. Superconducting magnetic energy storage (SMES):

It is a storage technology for a very short duration and not feasible for medium-scale applications. Its complexity lies in the need for a refrigeration system, transformers and converters, and a large infrastructure. This greatly increases the cost and makes more complicate the operation of the system. Moreover, this type of storage is not too adaptable to WDHS and does not contribute to a remarkable reduction in fuel consumption. For these reasons, it is excluded from the list of the studied technologies.

After excluding all the technologies mentioned above, it is proposed to use the compressed air energy storage system (CAES) to associate with the WDHS. Indeed, the CAES is adaptable for both sources of power generation (wind / diesel). Moreover, the CAES is an interesting solution to the problem of strong stochastic fluctuations of the wind power because it offers a high efficiency conversion (60-70% for a complete charge-discharge cycle), uses conventional materials which are easy to recycle and is able to make an almost unlimited number of cycles [24], [28].

8. Validation of the choice of compressed air energy storage using the performance index method

8.1 Performance index

The analysis of the techno-economic criteria such as cost, energy density, lifetime, energy efficiency of each technology, etc.., allows evaluating a «performance index» and developing a yields diagram of different storage technologies. The performance index is the measure of the applicability of a storage technique to a specified application taking into account the characteristics presented in section 6 (for example, cost, efficiency, simplicity, life time, maturity, self-discharging, reliability, environmental impact, operation constraints, energy and power capacity, adaptability with wind-diesel system, contribution to reduce of fuel consumption, etc.) [29]. For another application than the power supply of a remote area, the values of the performance index can be different.

8.2 *Method used to determine the performance index*

The determination of performance index is done using a decision matrix that helps to balance by a factor varying from 5 to 10% the importance of each characteristic of the storage system with regard to the specific requirements of the envisaged application. The development of this matrix takes into account the interaction between the selection criteria mentioned above, the reference data of storage technologies and the characteristics of WDHS and above the main objective: choice one technology that contributes to decrease the consumption fuel and GHG emissions of diesel generator.

In this study, more emphasis was given to cost, the contribution to reducing fuel and GHG emissions. A weight factor of 10% was then attributed for each of these criteria. By cons, the cyclability, autonomy, efficiency, simplicity, each has obtained a weighting equal to 7.5% for their medium importance. Finally, because their lower importance, the following criteria: safety, self-discharge, storage, reliability, maturity, operational flexibility, control, and the ecological response times were weighted by coefficient of 5 % for each (Figure 3).

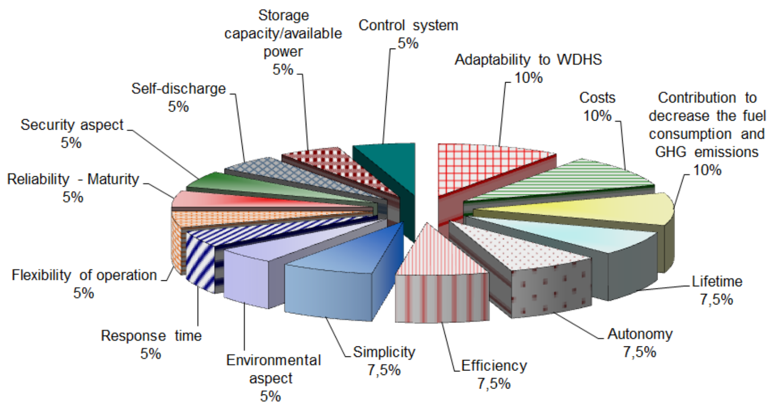

Figure 3. Allocation criteria in the decision matrix

Table 1. Elementary decision matrix for the criterion "adaptability to WDHS"

Adaptability to WDHS	PHS	CAES	FES	BES	RBES	HES	TES	SCES	SMES	Total
PHS		0	0	0	0.5	0	0	0	0	**0.5**
CAES	1		1	1	1	1	1	1	1	**8**
FES	1	0		0.5	1	0.5	0.5	0.5	0.5	**4.5**
BES	1	0	0.5		1	0.5	0.5	0.5	0.5	**4.5**
RBES	0.5	0	0	0		0.5	0	0.5	0.5	**2**
HES	1	0	0.5	0.5	0.5		0	0.5	0.5	**3.5**
TES	1	0	0.5	0.5	1	1		1	1	**6**
SCES	1	0	0.5	0.5	0.5	0.5	0		0.5	**3.5**
SMES	1	0	0.5	0.5	0.5	0.5	0	0.5		**3.5**

For each criterion, we attributed a value of either 0, 0.5 or 1 to each storage technology when comparing to another, respectively if the associated performance is worse (value of 0), equal (value of 0.5) or better (value of 1). In Table 1, we illustrate the comparison between the energy storage technologies with regard to the adaptability to the high penetration wind-diesel hybrid system. The analysis shows that flywheel is equivalent to batteries, supercapacitors, superconducting, thermal storage and hydrogen storage (coefficient of 0.5), while it is better (more adaptable to WDHS) than hydraulic storage and flow batteries (coefficient 1). On the other hand, the compressed air storage is more adaptable to SHED compared to the flywheel; the corresponding coefficient is then 0 for flywheel. The same method is applied to all the energy storage technologies for each of the 15 selection criteria, the results being 15 elementary decision matrixes corresponding to each criterion.

The global decision matrix assembles the coefficients attributed to each energy storage system for each elementary decision matrix associated to each of the 15 selection criteria. Considering the weight coefficients of every criterion in the calculation, we obtained the classification of performance of each used system. The elementary performance index (Figure 4) and overall performance index (Figure 5) can be obtained respectively from the elementary and overall matrix of decision by calculating the percentage of the total score obtained by each technology (global) and for each mentioned criteria (elementary) compared to the maximum total score (8) that a storage technology can be obtain. It is easy to establish from the Figure 6 that the compressed air energy storage system (CAES) answers to the choice criteria with the better performance index, approximately 82 %.

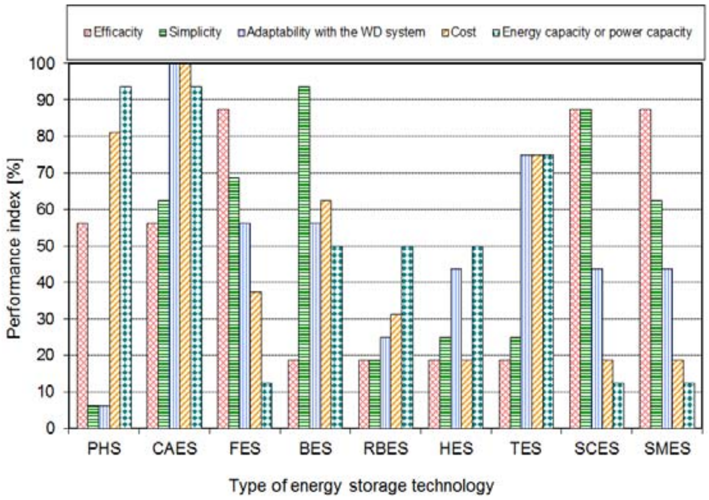

Figure 4. Comparison of the elementary performance index regarding to various criteria

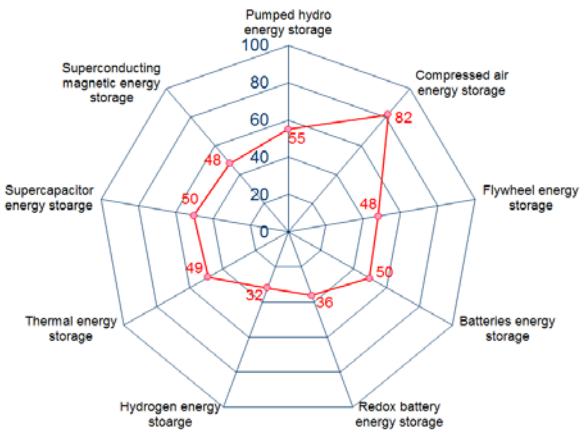

Figure 5. Global performance index of the different energy storage technologies

9. Conclusion

A comparative analysis of different storage technologies currently in use was effectuated according to several criteria such as cost, energy density, specific power, contributing to reducing fuel consumption and GHG emissions, the lifetime and efficiency of each technology. This analysis was served to determine the performance index of each storage technology based on the nature of the project application. The determination of the performance index of each technology represents, despite its subjectivity resulting from the use of the decision matrix, a solution where we have some difficulty to choose a technology and where the constraint of time does not achieve a detailed modeling of the studied systems. This method showed that the CAES answers to the choice criteria with a performance index approximately 82 %. Other systems are also more or less effective but at the cost, simplicity, adaptability to the WDHS, the contribution to reducing fuel consumption and GHG emissions and duration of life that there is some difference. For these reasons, CAES technology was adopted to associate with the wind-diesel hybrid system.

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