# Potential of a Hybrid Wind-Diesel-Compressed air system for Nordic Remote Canadian Areas

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**Abstract**

In Canada, off-grid power production is significant, with more than 200,000 people living in about 300 remote communities scattered across Yukon, the Northwest Territories, Nunavut, and other islands. Most of these isolated sites rely on diesel to generate electricity. The operation of these remote isolated grids run on a deficit in the order of hundreds of millions of dollars yearly and must therefore be subsidized by the government. Low and high penetration wind–diesel hybrid systems (WDS) have been experimented to reduce diesel consumption. In a previous article, we explored the re-engineering of current diesel power plants with the introduction of high penetration wind systems using compressed air energy storage (CAES). This is a viable alternative to increase the overall percentage of renewable energy and reduce the cost of electricity, to increase the diesel engine lifetime and efficiency and to decrease their fuel consumption and GHG emissions. In this paper, we present the operative principle of this hybrid system, its economic benefits and advantages. Finally, we apply this concept in the case of a Canadian Nordic village to demonstrate the real energetic, ecological and economic potential of this system.

## 1. Introduction

In most remote areas, the diesel generator is the main source of electrical energy. For these regions, the price in extending the electricity grid is very prohibitive and the remoteness highly majors the fuel price.

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The continuous decline of renewable energy prices and their increased reliability have led to an increased use of these resources for the electrical generation in remote areas.

In Quebec, in parallel with the rise of wind power, mainly in the form of large parks connected to the central grid of distribution, power supply via diesel units in remote areas still remains an unavoidable technical and financial challenge. Indeed, this electricity production method is relatively inefficient, expensive and responsible for the emission of large quantities of greenhouse gases (GHG). With the increase of fuel prices and freight, the financial losses are colossal [1]. These deficits, 133 million dollars per year according to Hydro-Québec, reflect the difference between the high costs of local production of electricity in these regions and the uniform price of electricity.

Paradoxically, most of these communities are situated in regions characterized by sufficient wind resource for a commercial exploitation. The use of wind-diesel hybrid system (WDHS) in these autonomous networks could reduce the operating deficits [2]. However, the profitability of the WDHS is reached at the condition of obtaining a high penetration of wind energy (PRWE) which is only possible through the use of storage systems [3]. After a thorough critical analysis of all the characteristics of the possible energy storage technologies, a solution that meets all the technical and financial requirements while ensuring a reliable electricity supply of these sites was proposed. It is the wind-diesel hybrid system with compressed air energy storage (WDCAS).

## 2. Why choose the compressed air energy storage for wind-diesel hybrid system?

Due to technical, economical and energetic advantages demonstrated by the compressed air energy storage (CAES) in hybrid systems at large scale use in the USA and Germany, we investigated the possibility to associate the wind-diesel with compressed air energy storage system for medium and small scale applications (isolated sites).

The choice of this system was not only based on the successes of large scale CAES system. The energy storage in the form of compressed air is suitable for both wind and diesel applications. Moreover, the CAES presents an interesting solution for the problem of strong stochastic fluctuations in wind power by offering a high efficiency conversion rate (60-70% for a complete charge-discharge cycle). It, also, uses conventional materials that are easy to recycle and can support an almost unlimited number of cycles [4].
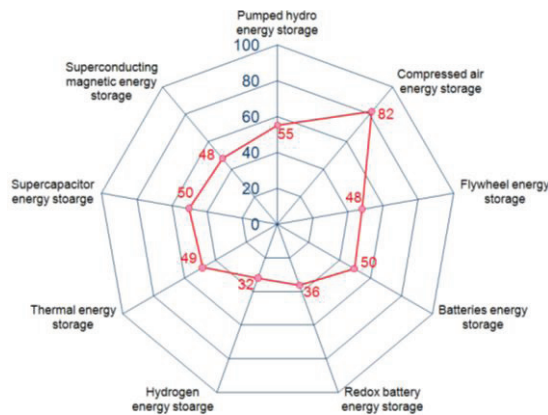


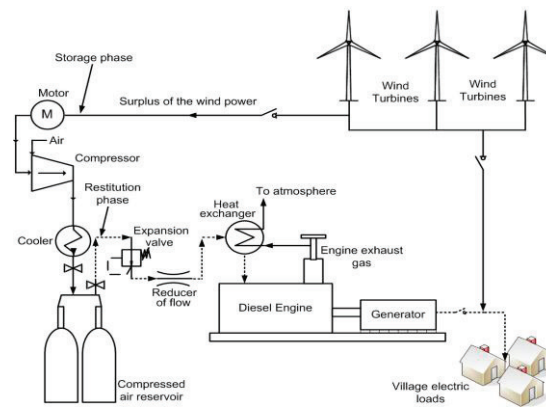Fig. 1:  Performance index of different energy storage systems          Fig. 2:  Illustration of the WDCAS system

A detailed study was realized to demonstrate 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 [5]. This study was based on the aggregation in a «performance index» of technical, economic and

environmental characteristics of various storage methods. The results of this analysis and the values of the performance index are illustrated in the figure 2 for different possible strategies of storage.

The performance index is the measure of the applicability of a technique of storage to a specified application [5]. For another application other than the power supply of a remote area, the values of the performance index can be different. The determination of the indication of performance is done using a decision matrix that helps to balance the importance of each characteristic (15 criteria, 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.) of the storage system with regard to the specific requirements of the envisaged application. It is easy to establish from the Figure 1 that the compressed air energy storage system (CAES) answers the choice criteria with a performance index of approximately 82 %.

## 3. Wind-diesel-compressed air system (WDCAS)

The WDCAS combined with diesel engine supercharging, will increase the wind energy penetration rate. Supercharging is a process consisting of a preliminary compression that aims to increase the density of the engine's air intake, in order to increase the specific power (power by swept volume). During periods of strong wind (when wind power penetration rate – WPPR, defined as the quotient between the wind generated power and the charge is greater than 1; WPPR>1), the wind power surplus is used to compress the air via a compressor and store it in a tank. The compressed air is then used to turbocharge the diesel engine with the two-fold advantage of increasing its power and decreasing its fuel consumption. The diesel generator works during periods of low wind velocity, i.e., when the wind power is not sufficient to sustain the load (Fig. 2).

WDCAS represents an innovative concept designed to overcome most of the technical, economic and social barriers that face the deployment of wind energy in isolated sites [6]. Indeed, implementation costs are minimized and reliability is increased by using the existing diesel generators. Our WDCAS solution is threefold: modification and adaptation of the existing engines at the intake level, addition of a wind power station and addition of an air compression and storage system.

## 4. Advantages of an additional turbocharging with stored compressed air

All the diesel engines that are used in remote Canadian areas are already equipped with a supercharging system via a turbocharger. However, this type of system loses its advantages during operation at low regime because its efficiency is directly related to the quantity of exhaust gases. To understand the advantage of an additional turbocharging of diesel engine and the operation limits of a turbocharger, we present in Figure 3 an example which compares a diesel engine in two functioning modes: atmospheric (without turbocharger) and turbocharged.

Figure 3 shows that as compared to an atmospheric diesel engine with an engine capacity of 10 L, supercharging can increase the values of the indicated efficiency of the engine (maximal efficiency = 45%) and extend the operating range in the area of high efficiency thanks to the large permissible quantity of air into the engine. For a load of 600 N.m, the efficiency of the supercharged engine is about 38% compared with that of atmospheric engine (14%), i.e., an increase about 170%. On the other hand, increasing the applied load on the engine triggers a degradation of the diesel performance due to the operation limits of the turbocharger and to the increase of the heat loss through the cylinder walls. However, this does not exclude the fact that the efficiency for high loads are better through supercharging as compared to the efficiency obtained with atmospheric engine (an increase about 64% for a load of 1200 N.m).

The Figure 3 also shows that the compression ratio reaches its maximal value (Fig. 3) only for the highest loads (this corresponds to high flow and pressure of exhaust gas). This delay to reach the maximal pressure of the compressed air at the engine intake will delay the achievement of the maximal power of the turbocharged engine. The objective of the additional supercharging via the stored compressed air is, then, to maximize the overall efficiency of the diesel engine (Fig. 3), by several improvements:

1) Improving the combustion efficiency by operating the engine at all times with an optimal air/fuel ratio, which does not allow the turbocharger to operate alone.

2) Reducing the pumping losses for the low pressure loop of the thermodynamic cycle of diesel engine to increase the work supplied for the same quantity of burned fuel.

3) Increasing the specific power (power per swept volume unit) of the diesel engine and its performance.

4) Increase the intake pressure at a level which allows a decrease of the fuel quantity injected while maintaining the same maximal pressure in the cylinder of the engine. This allows decreasing the mechanical and thermal constraints due to the supercharging.
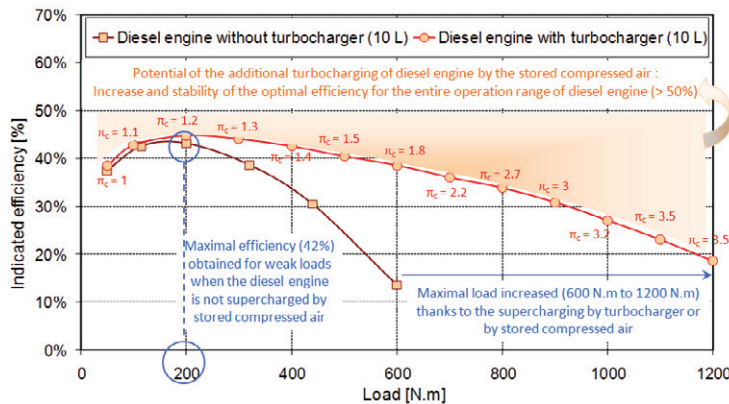


Fig. 3: Potential of the additional turbocharging of diesel engine by the stored compressed air
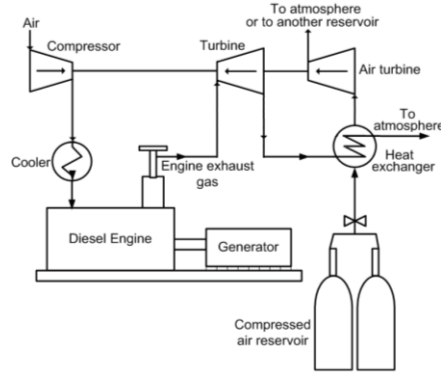


Fig.4: Illustration of the WDSAC with the CAES turbine directly connected to the turbocharger shaft

## 5. How to supercharge more the diesel engine?

Several methods available to supercharge the diesel engines using the stored compressed air (SAC), such as:

*1) Use of an air turbine directly connected to the turbocharger shaft (Fig. 4)*
*2) Two-stage turbocharge*
*3) Admission of compressed air directly in the compressor*
*4) Admission directly in the engine (Fig. 5)*
*5) Hyperbar turbocharger*
*6) Tubocharger based on a pressurized LENOIR cycle*
*7) Turbocharging with downsizing*

In this study, to improve the performances of the WDCAS system and evaluate the fuel economy obtained thanks to the use of CAES, we explore the turbocharging of diesel engine with the direct admission of the compressed air in the engine using the intake valve.

A stationary model, including 8 main blocks, is necessary to represent the diesel engine. Each of these blocks corresponds to a component that operates a change of the thermodynamic state of the compressed air (CA) or exhaust gases (EG) in the circuit. These components are the air filter (AF), the admission

collector (AC), the compressor (C), the heat exchanger (HEX), the combustion chamber (CC), the exhaust collector (EC), the gas turbine (GT) and the load (LD). The details of models for these components will be presented in a future paper. In this paper, we emphasize on the model of indicated efficiency of diesel engine as it is required to compute the indicated power [7], [8] and [9]:

$$P_{DE} = p_{ci}\eta_i\dot{m}_f \tag{1}$$

where $p_{ci}$ is the indicated lower calorific value of the fuel, $\dot{m}_f$ is the fuel mass flow injected in cylinders and $\eta_i$ the indicated efficiency.
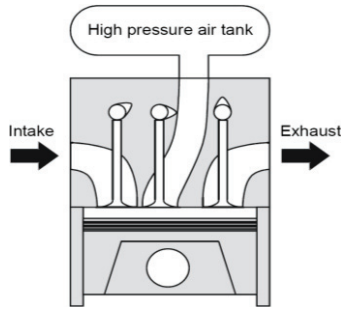


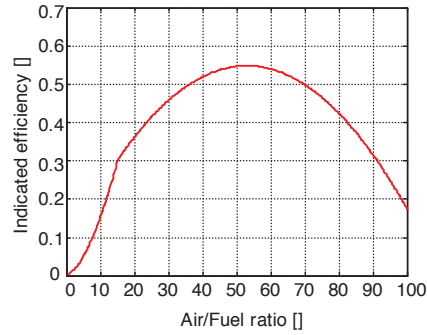Fig.5: Admission of compressed air directly in the engine



Fig. 6: Variation of indicated efficiency with the air/fuel ratio

Since the engine will operate at constant rotation speed and to take into account the physical limits of the combustion, we adopted a quadratic model of the following form [10]:

$$\begin{cases} \eta_i = a + b\lambda + c\lambda^2 & \text{if } \lambda \geq \lambda_{st} \\ \eta_i = \left(a + b\lambda + c\lambda^2\right) \cdot \dfrac{\lambda}{\lambda_{st}} & \text{if } \lambda < \lambda_{st} \end{cases} \tag{2}$$

where $a$, $b$, $c$ are constants, $\lambda_{st}$ is the stoichiometric air/fuel ratio equal to 14.7 for the diesel fuel and $\lambda$ is the air/fuel ratio defined by :

$$\lambda = \frac{\dot{m}_{in\_DE}}{\dot{m}_{f\_DE}} \tag{3}$$

$\dot{m}_{in\_DE}$ is the mass flow of air entering the engine. It is defined as follows:

$$\dot{m}_{in\_DE} = \eta_{v\_DE} \frac{C_{y\_DE}}{4\pi} \omega_{DE} \frac{p_{in\_DE}}{r T_{in\_DE}} \tag{4}$$

Here, $p_{in\_DE}$ is the inlet pressure of diesel engine, $T_{in\_DE}$ is the inlet temperature of the diesel engine, $C_{y\_DE}$ is the total swept volume, $r$ is the constant of ideal gas, $\omega_{DE}$ is the diesel engine rotation speed and $\eta_{v\_DE}$ is the volumetric efficiency of the engine, modeled by [11]:

$$\eta_{v\_DE} = \alpha_0 + \alpha_1\omega_{DE} + \alpha_2\omega_{DE}^2 \tag{5}$$

where $\alpha_i$ are constants.

Figure 6 represents the variation of indicated efficiency with the air/fuel ratio. Three zones can be distinguished in the figure 6: the first (in the lift) corresponds of the low efficiency zone due to the degradation of the combustion quality. The second (in the right) represents the degradation of

performances due to increased losses by heat transfer between the combustion gases and the cylinder walls. The third (in mid) represents the maximum efficiency and which corresponds to the optimal air/fuel ratio ( $\lambda_{opt} \approx 53$ ). In this study, the diesel engine will operate with a maximum efficiency obtained from an air/fuel ratio always maintained optimal thanks to stored compressed air.

## 6. Case study - Operation strategy of WDCAS

To estimate the potential gain on a target site, we recovered wind speed data every hour and the hourly electrical load of the diesel engine on the site of the village of Tuktoyaktuk in the Northwest Territories of Canada on the Arctic coast. The maximum and average electric loads of this village are respectively 851 kW and 506 kW. Initially, the village's electricity is supplied by 2 diesel generators, each having 544 kW as maximal power. To these generators a wind plant composed of 4 wind turbines of type Enercon, each having a nominal power equal to 335 kilowatts, a total power equal to 1340 kW was added.

Two strategies for the operation of WDCAS were explored. The following strategy was adopted for this study because it gives more advantages to power supplied by wind turbine as compared to that produced by diesel, especially during periods of average penetration rate of wind energy. It is defined as follows:

$$
\text{if } P_{WT} < P_{CH} \Rightarrow
\begin{cases}
\text{if } P_{CH} < 30\% P_{n\_DE} \Rightarrow
\begin{cases}
P_{DE} = 30\% P_{n\_DE} \\
P_{SS} = P_{EX\_DE} \\
P_{CH} = P_{WT} + \left(30\% P_{n\_DE} - P_{SS}\right)
\end{cases} \\[2em]
\text{if } 30\% P_{n\_DE} < P_{CH} < P_{n\_DE} \Rightarrow
\begin{cases}
P_{SS} = 0 \\
P_{CH} = P_{DE} + P_{WT}
\end{cases} \\[2em]
\text{if } P_{CH} > P_{n\_DE} \Rightarrow
\begin{cases}
P_{SS} = 0 \\
P_{CH} = P_{DE\_1} + P_{DE\_2} + P_{WT} \\
P_{DE\_1} = P_{DE\_2} = \frac{1}{2}\left(P_{CH} - P_{WT}\right) \\
2 \text{ engines in operation}
\end{cases}
\end{cases}
$$

$$
\text{if } P_{WT} = 0 \Rightarrow P_{DE} = P_{CH} \Rightarrow
\begin{cases}
\text{if } P_{CH} < 30\% P_{n\_DE} \Rightarrow
\begin{cases}
P_{DE} = 30\% P_{n\_DE} \\
P_{SS} = P_{EX\_DE} \\
P_{CH} = 30\% P_{n\_DE} - P_{SS}
\end{cases} \\[2em]
\text{if } 30\% P_{n\_DE} < P_{CH} < P_{n\_DE} \Rightarrow
\begin{cases}
P_{SS} = 0 \\
P_{CH} = P_{DE} \\
1 \text{ only engine in operation}
\end{cases} \\[2em]
\text{if } P_{CH} > P_{n\_DE} \Rightarrow
\begin{cases}
P_{SS} = 0 \\
P_{CH} = P_{DE\_1} + P_{DE\_2} \\
P_{DE\_1} = P_{DE\_2} = \frac{1}{2} P_{CH} \\
2 \text{ engines in operation}
\end{cases}
\end{cases}
$$

$$\text{if } P_{WT} > P_{CH} \Rightarrow \begin{cases} P_{DE} = 0 \\ P_{SS} = P_{EX\_WT} \\ P_{CH} = P_{WT} - P_{SS} \end{cases}$$

where, $P_{WT}$ and $P_{DE}$ are the power generated by wind turbine and that of the diesel engine respectively. $P_{EX\_WT}$ is the excess wind power, $P_{SS}$ and $P_{CH}$ are the respective powers absorbed by the storage system and that of the electrical load. $P_{DE\_1}$ and $P_{DE\_2}$ are the respective powers of the first and second diesel engine respectively. $P_{n\_DE}$ is the nominal power of diesel engine.

The diesel engine turbocharged by the compressed air stored will function with maximal efficiency ( $\eta_{i\_DE\_max} \cong 56\%$ ) obtained for optimal air/fuel ratio ( $\lambda_{opt} \cong 53$ ). Achieving this performance is guaranteed by the additional power due to the compressed air injected into the cylinders of diesel engine. The details of the calculation of the diesel engine power are presented in my Ph.D. dissertation [12].

We estimated fuel consumption, greenhouse gases (GHG) emissions and maintenance cost of diesel engines for different scenarios: diesel only, wind-diesel hybrid system (WDHS) without CAES and wind-diesel hybrid system with CAES, over a period of one year (2007 year's). Figures 7 to 15 illustrate the results.

## 7. Results and discussion

Figures 7 and 8 represent the profile of the average wind speed corrected to hub height of wind turbines, the profile of the monthly electrical load of the village, the variations of wind power, the variations of power supplied by diesel generators before and after hybridization with the wind turbines, the operation frequency of diesel engines after hybridization and the profiles of the power directed towards the storage system and that absorbed by the compressor. These figures show that the maximal average consumption of the village occurs during fall and winter seasons due to the increase of the electric load for the heating. Unfortunately, the highest wind speed is registered during the spring and summer seasons where the average electricity consumption decreases to approximately 200 kW in comparison with that of winter.
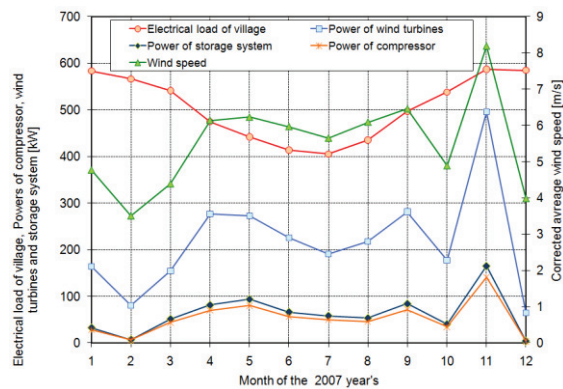


Fig. 7: Average wind speed and power profiles of the: electrical load, wind turbines, compressor and energy storage system
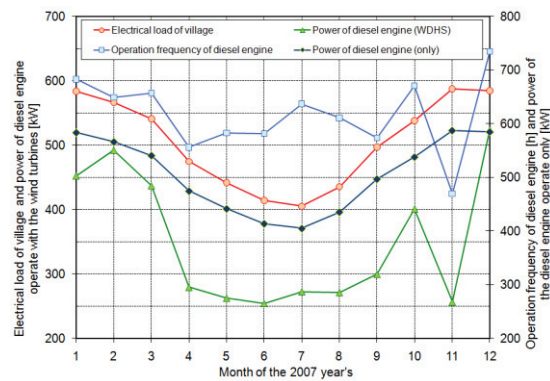
Fig. 8: Operation frequency and power curve of diesel engines and profile of the electrical load

Figure 9 shows the operation frequency of diesel engines after the hybridization with the wind turbines. The number of functioning hours of diesel engines strongly depends on the availability of the wind power

and the level of the electric load of the village. During 2007, the hybridization would have allowed the operation of a single engine during 5,887 hours (68%), of two engines during 1,521 hours (17%) and stop both diesel generators approximately 1,352 hours (15%).
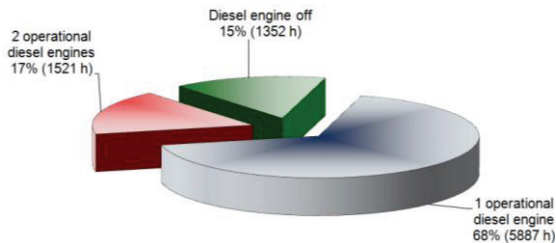


Fig. 9: Operation frequency of diesel engines after the hybridization with the wind turbines
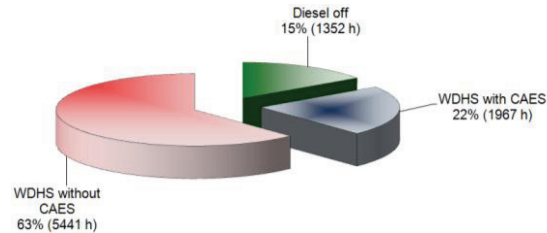


Fig. 10: Operation frequency of diesel engines according to their supercharging mode

Figure 10 represents the operation frequency of diesel engines according to their supercharging mode (with or without CAES). This figure shows that hybridization allows the functioning of diesel engines supercharged by stored compressed air during 1,967 hours (22%). During 5,441 hours (63%), the diesel engines are operating without CAES and they are stopped for 1,352 hours.

Figure 11 represents the monthly frequency of functioning in each exploitation scenario (diesel only, WDHS without CAES or with CAES). It is interesting to note that the operation frequency of the two diesel engines heavily depends on the season (highest in the winter and low during the summer). Furthermore, the hybridization wind-diesel with CAES allows a remarkable decrease of the frequency of use of the 2 engines as compared with the diesel only mode.

Figure 12 shows the operation frequency for each of the two diesel engines. Compared with the base line scenario, the hybridization between wind energy and diesel engines without CAES reduces by 15.4% the annual operation hours of the first engine and about 49% for the second engine. However, a WDHS with CAES does not affect the operation frequency of the first motor, compared to that obtained with WDHS without CAES, where it work 7408 hours throughout the year. However, the effects of CAES appears on the operation duration of the second engine which is 1521 approximately hours, saving hours of operation- about 57% as compared to that obtained in diesel only mode and almost 15% as compared to the WDHS without CAES mode.
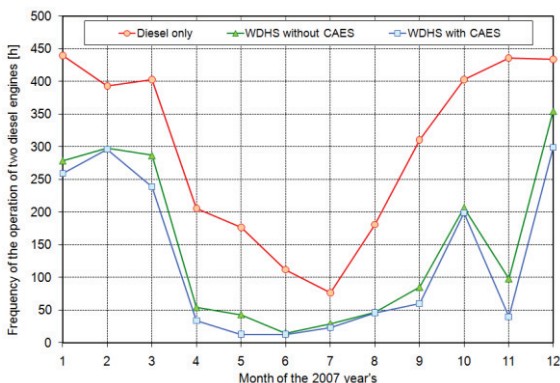


Fig. 11: Monthly frequency of functioning in each exploitation scenario (diesel only, WDHS without CAES or with CAES)
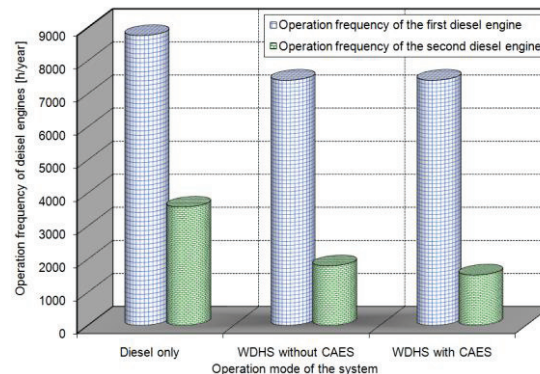


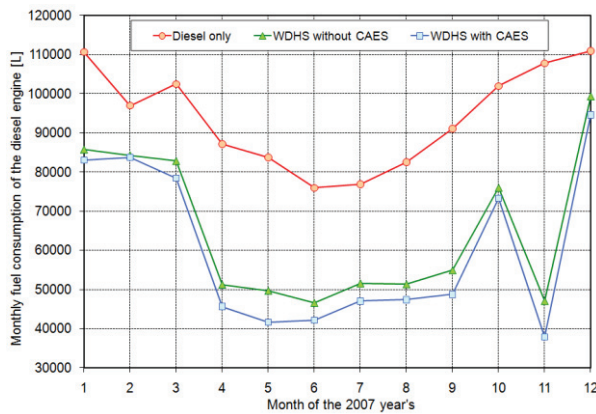Fig. 12: Operation frequency for each of the two diesel engines

Fig. 13: Monthly consumption of fuel along a 2007 year's

Figure 13 shows the monthly consumption of fuel during a year (2007). Compared with the base line scenario, the use of WDHS without CAES allows fuel reduction varying from 11,577 litres (minimal value) in December to 60,741 litres (maximal value) in November. On the other hand, a WDHS with CAES will significantly increase this economy with a minimum fuel saving of 13,200 litres (February) and a maximum of 69,921 litres (November).

Figure 14 illustrates the annual fuel savings. The hybridization between wind energy and diesel engines without CAES reduces by 347,615 litres the annual fuel consumption (31%) while with CAES, this reduction increases to 36% (404,564 litres). This quantity (36%) is equivalent to 1132.78 tons of $CO_2$ or the annual emission of 167 automobiles and light trucks traveling 15,000 km/year.
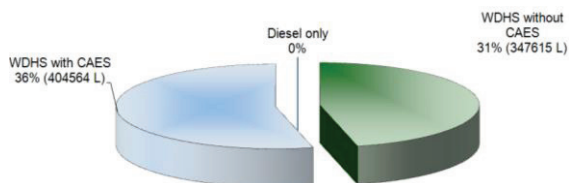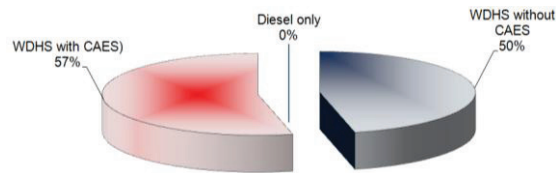


Fig. 14: Annual fuel savings



Fig. 15: Annual reduction of maintenance and operation costs

The estimation of the annual reduction of maintenance and operation costs, based on the reduction of operation time of the two diesel engines, is represented in Figure 15. The base line for comparison is the scenario without hybridization, where no savings in the cost of maintenance can be realized. The WDHS without CAES allows 50% reduction while with CAES, this rate increases to 57%. It is important to mention that the supercharged diesel engine by compressed air stored allows operating with a single diesel engine, whatever the load of the village. On the other hand, a permutation between the two supercharged engines will be necessary to avoid the blocking of some mechanical moving pieces of the engine.

## 8. Conclusion

In spite of the existence of several techniques of storage intended for applications in isolated sites (Lithium - ions batteries, hydrogen storage plus fuel cell), the proposed design remains the most effective, the least polluting, the least expensive and the most successful. Indeed, although the new batteries are more durable and more efficient, they have remained expensive and require converters (AC-DC), control systems and regular maintenance. To that, recycling issues at the end of their lifetime must be catered for.

In the meantime, the hydrogen storage system combined with fuel cell to produce electricity, is characterized by a prohibitive price of the electrolyser and the low overall efficiency (about 35%) without forgetting that the use of the hydrogen as fuel requires internal interventions on the ignition system of existing diesel engines (already in place), which is avoided with the proposed concept. Due to technical, economic and energetic advantages demonstrated for the use at large scale in USA and Germany of the compressed air energy storage combined with the wind-gas turbines in hybrid system, we investigated the possibility to associate the wind-diesel with compressed air energy storage system for electricity supply of remote areas.

The WDCAS allows not only increasing the penetration rate of wind energy but a fast starting up of the diesel engine. This system is efficient in terms of cost and GHG reduction. To demonstrate the real potential of this system, the WDCAS is applied for the case of Tuktoyaktuk (northern Canadian village). This village is characterized by an annual wind speed that does not exceed 5.5 m/s. Despite this low average wind speed, remarkable savings may be obtained through the use of compressed air, by avoiding the consumption of large fuel quantities and by allowing the use of a single diesel engine (instead of two) for a long period of the year. This allows not only reducing the exploitation deficit of diesel engines supplying the autonomous networks in remote areas, but also to prolong engine life-cycle and reduce maintenance costs. However, in future works, the calculation of the energy cost (kWh), based on the investment cost and the purchase of new equipment (wind turbines, CAES equipment, etc.) will allow determining the system's economic viability for remote applications. Finally, further investigation and analysis, as well as building and testing a prototype, are required to validate the present conclusions.

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