Étude de faisabilité d'un système éolien diesel avec stockage d'air comprimé

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AVANT-PROPOS

Ce travail de maitrise a été réalisé au Laboratoire de Recherche en Énergie Éolienne (LREE) à l'Université du Québec à Rimouski (UQAR). Il est présenté sous la forme d'un mémoire par articles. Le premier chapitre consiste en une introduction aux logiciels d'analyse financière, de sensibilité, de risque et étude d'impact environnementale générale disponibles sur le marché, leurs points forts et points faibles, le modèle théorique pour le développement du logiciel concernant le système éolien diesel avec stockage d'air comprimé (SHEDAC), et enfin une étude de cas pour valider ce dernier.

Le deuxième article est une application du logiciel sur un cas réel, le camp minier Esker dans le nord du Québec.

RÉSUMÉ

Le Système Hybride Éolien-Diesel avec Stockage d’Air Comprimé (SHEDAC) utilise l’hybridation pneumatique pour remplacer la consommation des combustibles fossiles par de l’énergie renouvelable, plus particulièrement de l’énergie éolienne. Le surplus de l’énergie éolienne est utilisé pour comprimer et stocker de l'air qui est utilisé ensuite pour suralimenter le moteur diesel.

Le mémoire de maîtrise est constitué de deux articles scientifiques. Le premier article présente le développement d’un logiciel dédié à l’étude de faisabilité d’un système éolien-diesel avec stockage d’air comprimé. Cette étude est basée sur l’analyse des coûts et des revenus, des coûts des équipements (éolienne, moteur diesel, système de stockage d'air). Elle est complétée par une analyse de sensibilité aux différents paramètres, une analyse des risques et des émissions des gaz à effet de serre (GES).

Le deuxième article est une application de ce logiciel pour l’installation d’un système SHEDAC au camp minier Esker au Québec en remplacement des sources actuelles de production d’énergie. L’utilisation du stockage d’air comprimé à l’aide d’un système SHEDAC est le plus rentable par rapport à l’utilisation de l'énergie éolienne seule ou d'une centrale thermique au diesel seule ou des deux combinées. Avec une valeur actuelle nette et un taux de rendement interne plus élevés, cette solution permet d’obtenir le plus bas coût de l'énergie pour cette région éloignée.

Mots-clés: Énergie éolienne, système hybride éolien-diesel, stockage d’air comprimé, Valeur actuelle nette, Taux de rendement interne, Coût de l'énergie

ABSTRACT

The Wind–Diesel-Compressed Air Storage System (WDCAS) technology uses pneumatic hybridization to replace the use of fossil fuels by renewable energy, especially wind power. The surplus of wind energy is used to compress and store air that is then used to supercharge the diesel engine.

This Master's thesis consists of two scientific articles. The first article presents the development of a software dedicated to the feasibility study of a wind-diesel system with compressed air storage. This study is based on analysis of costs and revenues, equipment costs (wind, diesel engine, and compressed air storage system). It is completed by a sensitivity analysis of various financial parameters, a risk analysis and emissions of greenhouse gases (GHGs).

The second paper is an application of this software to a WDCAS installation at the Esker mining camp in Quebec, in replacement of the current sources of energy production. The use of compressed air storage in the WDCAS is the most cost effective compared to using only the wind power or diesel engines or both combined. With a high net present value and a high internal rate of return, this solution provides the lowest cost of energy to this remote region.

Keywords: Wind Power, wind-diesel hybrid system, compressed air storage, Net present value, internal rate of return, Cost of Energy

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LISTE DES ABRÉVIATIONS, DES SIGLES ET DES ACRONYMES

WPPR	Wind Power Penetration Rate
WDCAS	Wind–Diesel-Compressed Air Storage System
CAES	Compressed Air Energy Storage
GHG	Green House Gas
WDS	Wind Diesel Hybrid System
GUI	Graphical User Interface
IRR	Internal Rate of Return
NPV	Net Present Value
NPC	Net Present Cost
IP	Index of Profitability
COE	Cost Of Energy
CFD	Computational Fluid Dynamics

CHAPITRE 1
INTRODUCTION GENERALE

1.1 GENERALITES SUR LA PRODUCTION D'ENERGIE DANS LES SITES ISOLES AU CANADA

1.1.1. Mise en contexte des sites isolés au Canada

Au Canada, 200,000 habitants abritent 300 communautés éloignées (Yukon, Nunavut, les Territoires du Nord-Ouest) [1].

La Figure 1.1 indique les communautés éloignées et les réseaux de distribution électriques principaux. On observe ainsi l'écartement des sites isolés des lignes de distribution. Il est aussi mis en évidence que le Québec regroupe plusieurs un nombre non négligeable de sites isolés.

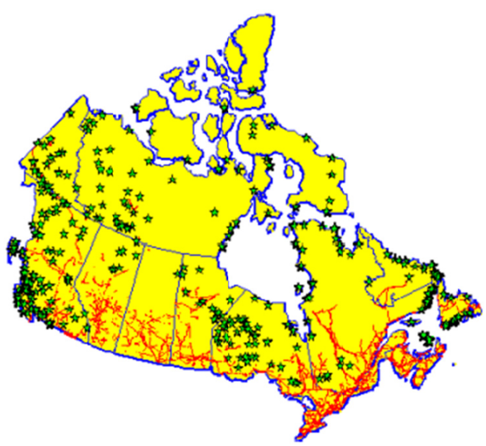

Figure 1.1: Cartes des communautés isolées au Canada (étoiles vertes) et des principaux réseaux de distribution électriques (en rouge) [2]

Les communautés isolées abritent de nombreuses installations techniques (tours et relais de télécommunication, systèmes météorologiques…), touristiques (pourvoiries, chalets…), agricoles et piscicoles qui ne sont pas connectées aux réseaux de distribution principaux. Ceci montre qu'il existe une demande d'approvisionnement énergétique importante dans ces zones. Ainsi, il faut envisager des solutions pour résoudre les limites énergétiques auxquelles font face les sites isolés [2] [3] [4] [5].

1.1.2. Problématiques des sites isolés

Vu l'éloignement, les communautés isolées ont un accès difficile au réseau de distribution principal d'électricité ou de gaz. Cette situation s'explique par la localisation géographique (montagnes, îles…) de ces sites qui empêche ou rend trop onéreux le raccordement aux réseaux principaux. Ces grands coûts sont dus à l'installation des lignes électriques sur des distances trop importantes ainsi qu'aux pertes qui en découlent lors de la distribution de l'électricité [6].

Pour ces raisons, ces communautés doivent produire et consommer leur propre énergie. Malheureusement, la principale source d'électricité dans la plupart de ces régions provient de génératrices diesel. Même s'il s'agit d'une source fiable, stable et continue en énergie, son utilisation entraine trois problèmes principaux : énergétique, économique et environnemental.

Dans la province du Québec, cette capacité d'énergie électrique provenant du diesel s'élève à 144 MW et les dernières estimations projetaient ce chiffre à presque 160 MW pour l'année 2015 [7].

Malgré la fiabilité de ce combustible, les sources d'approvisionnements deviennent de plus en plus réduites et la demande ne cesse d'augmenter. Le carburant n'étant pas disponible dans ces sites, il faut le transporter, augmentant ainsi les coûts qui varient en fonction de l'éloignement des sites ainsi que du moyen de transport (voies terrestres, aériennes ou maritimes).

D’un point de vue de l’efficacité du système, les génératrices diesel ne sont pas très efficaces à des basses capacités, entrainant l’usure et de la surconsommation de carburant [8]. Outre ces problèmes qui tendent à être accentués par la détérioration et le vieillissement de ces machines, la génération de gaz à effet de serre (GES) par ces dernières est non négligeable [7]. En conséquence, l’impact environnemental lié à l’usage des génératrices diesel est significatif.

Ainsi, l’utilisation des génératrices diesel seules est une solution qui doit être améliorée par l’apport des sources renouvelables pour la production d’énergie dans les sites isolés.

1.1.3. Solutions énergétiques envisagées et développées

Au Canada et plus précisément au Québec, la diversité du territoire permet de profiter de différentes ressources dont les principales sont l’hydraulique, l’éolien et le solaire. Ces dernières sont bien adaptées pour les sites isolés.

Même si les coûts d’installation des systèmes à énergies renouvelables sont plus onéreux, les recherches et le développement ont conduit à une chute importante des prix qui facilite l’implantation de ces systèmes dans les sites isolés.

Bien que le prix des installations à énergies renouvelables baisse au cours des années, la source d’énergie renouvelable est fluctuante [9], donc non fiable pour l’approvisionnement stable en électricité.

Ainsi, l’utilisation seule des énergies renouvelables pour la production d’électricité dans les zones isolées n’est pas envisageable, c’est pourquoi il a été indispensable d’imaginer des systèmes hybrides d’énergie, utilisant à la fois des ressources renouvelables et fossiles avec ou sans des moyens additionnels de stockage.

Un système hybride exploite au moins deux types de ressources à des fins de production d’électricité (ex : éolien-diesel, éolien-photovoltaïque, éolien-diesel-stockage, etc.). De plus, un système hybride destiné pour l’électrification des régions isolées doit assurer en tout temps un approvisionnement électrique constant et suffisant à la charge, en optimisant les ressources énergétiques disponibles.

C'est pourquoi les systèmes actuellement réalisés ou en développement utilisent une source conventionnelle (génératrice diesel) et une source renouvelable (éolien, solaire…) avec, éventuellement, un système de stockage.

1.1.4. Systèmes hybrides éolien-diesel

L'utilisation de l'énergie éolienne en supplément des génératrices diesel est une alternative pour la production d'électricité dans les zones isolées. Ce choix est justifié par le fait que dans des zones souvent désertes, l'implantation d'une ou plusieurs éoliennes ne présente pas de contraintes particulières [10] [11] [12]. D'autre part, la complémentarité entre le besoin de réduire l'utilisation des diesels et le grand potentiel éolien disponible dans ces sites est un grand avantage en faveur de l'utilisation de l'énergie éolienne.

Dans un système hybride de production d'énergie, l'utilisation du stockage permet de reporter l'utilisation de l'énergie excédentaire qui provient de l'un des sous-systèmes. Cette énergie stockée est restituée, directement ou indirectement, sous forme d'électricité [13]. Généralement, des batteries électrochimiques viennent compléter le jumelage éolien-diesel. La bonne connaissance de ce type de stockage (notamment dans le domaine automobile) explique pourquoi la plupart des études ont souvent favorisé son usage [14] [15] [16] [17].

Bien que les batteries soient les composants les plus utilisés pour le stockage de l'énergie électrique, elles présentent des problèmes techniques et économiques [16] [18] [19] [20].

Le stockage sous forme d'air comprimé représente une alternative intéressante pour les systèmes éolien-diesel parce qu'elle permet, à travers l'hybridation pneumatique, d'améliorer les performances du diesel lorsque son fonctionnement est requis. En effet, par rapport aux facteurs comme le coût, la simplicité d'utilisation, la contribution à la diminution de la consommation de carburant et des émissions de GES, la durée de vie et autres facteurs technico-économiques, cette technologie semble optimale en comparaison avec les autres systèmes de stockage. Plusieurs recherches récentes ont porté sur l'élaboration et l'optimisation d'un système hybride éolien-diesel avec stockage par air comprimé (SHEDAC) [3] [21] [22] [23] [24] [25].

1.2 ÉTAT DE L'ART SUR LES SYSTEMES HYBRIDES AVEC STOCKAGE

L'hybridation entre des sources d'énergies renouvelables et des sources non renouvelables (génératrices diesel) avec ou sans stockage est une solution pour la production d'électricité dans les zones isolées. Depuis les dernières années, plusieurs projets de recherche et industriels dans le secteur des systèmes hybrides ont été réalisés. Il est donc pertinent de faire un état des connaissances sur le sujet, afin de présenter les avancements réalisés et d'en extraire les forces et les faiblesses de ces systèmes.

Il est important de rappeler que dans les systèmes hybrides il est préférable d'avoir une unité de stockage, pour emmagasiner l'énergie excédentaire produite. Dans cet état de l'art nous présentons :

- Le choix des technologies alternatives aux génératrices diesel
- Le type de stockage à envisager
- La stratégie de contrôle des flux énergétiques dans ces types de systèmes

1.2.3. Implantation de sources énergétiques additionnelles

L'éolien se présente comme la source la plus adéquate comme alternative aux génératrices diesel. Cependant, l'implantation d'autres sources d'énergies renouvelables comme le solaire photovoltaïque ou l'hydroélectricité restent l'objet de nombreuses études.

L'utilisation de plusieurs sources renouvelables doit permettre de diminuer la part de la source non renouvelable, dans ce cas la génératrice diesel à l'intérieur un système.

Cependant, une telle configuration est très couteuse puisque cela nécessite un investissement et un espace supplémentaires ainsi qu'une gestion de production et de stockage plus complexe. C'est pour cela que le couplage avec une centrale diesel reste peu répandu [26] [27] .

Dès le début des années 2000, des études ont été réalisées pour examiner la faisabilité de l'hybridation avec l'énergie solaire et la façon de dimensionner et optimiser un tel système [9] [28]. C'est ainsi que le solaire photovoltaïque se présente comme la meilleure énergie complémentaire à l'éolien pour l'hybridation avec des génératrices diesel.

Plusieurs articles ont été publiés sur le dimensionnement et la modélisation d'un système photovoltaïque notamment pour la production d'électricité en Afrique et en Moyen-Orient où l'énergie solaire est suffisamment abondante [29] [30].

Dernièrement, une étude récente a démontré l'efficacité d'un système hybride éolien-photovoltaïque-diesel avec stockage par batterie ainsi qu'une gestion optimale des flux énergétiques d'un tel système [31].

1.2.4. Incorporation d'unités de stockage d'énergie – L'air comprimé comme solution

Dans n'importe quel système de production d'électricité, le stockage est une partie intégrante du système. Le stockage, quelle que soit sa forme, permet d'emmagasiner l'énergie excédentaire, lorsque la demande en énergie est plus faible que la production. De plus le stockage permet de diminuer la part de l'énergie produite par les génératrices diesel en la substituant à l'énergie stockée.

Cette énergie stockée est restituée, directement ou indirectement, sous forme d'électricité [32]. La technologie de stockage la plus répandue jusqu'à maintenant est le stockage électrique par batteries électrochimiques. La bonne connaissance de ce type de stockage explique pourquoi la plupart des études ont souvent favorisé son usage [31] [33] [34] [35]. Toutefois, les autres de technologies de stockage existantes ont fait l'objet de plusieurs recherches, l'objectif étant de trouver une façon de stocker le maximum d'énergie pour un coût réduit et le minimum d'encombrement [36] [37] [38].

Ainsi, les principaux types de stockage d'énergie sont les suivants [38]:

a) Le stockage sous forme chimique. Ce système est basé sur des réactions électrochimiques [28] [39] ;

b) Le stockage sous forme d'énergie potentielle de pesanteur. Ce type de stockage est très utilisé dans les centrales hydrauliques, l'eau est pompée durant les périodes creuses afin d'emmagasiner l'énergie et elle est turbinée lors des périodes de pointe afin de produire de l'électricité [21] [25] ;

c) Le stockage sous forme d'énergie cinétique. L'énergie est stockée à travers la rotation d'un élément autour d'un axe (volant d'inertie) [21] [25] [24] [22] ;

d) Le stockage sous forme d'hydrogène. Mettant en œuvre une pile à combustible, basé sur des réactions d'hydrogène, l'utilisation de ce système est principalement étudiée dans le domaine de l'automobile [21] [25] ;

e) Le stockage sous forme thermique. Ce procédé peut être mis en œuvre de différente façon : lors du chauffage d'un corps avec changement d'état (chaleur latente) ou lors du chauffage d'un corps sans changement d'état (chaleur sensible). Cette technologie se retrouve dans le fonctionnement des centrales solaires thermiques [21] [25] ;

f) Le stockage sous forme d'énergie potentielle de pression. Ce procédé constitue à emmagasiner l'énergie sous forme d'air comprimé à l'aide de réserves de stockage naturelles ou artificielles [21] [25].

Dans le but de dégager une solution optimale parmi la multitude de procédés existants, une étude, établie par plusieurs laboratoires au Québec, a présenté une analyse paramétrique entre neuf technologies de stockage [40] [41]. Visant à savoir quel type de stockage serait le plus adapté à un système éolien-diesel, cette étude a démontré que le stockage par air comprimé se présente comme la meilleure solution.

En effet, cette solution est la moins couteuse, la plus simple, et celle qui contribue le plus à la diminution de la consommation de carburant et des émissions de GES. Elle est optimale du point de vue de durée de vie et d'autres facteurs technoéconomiques par rapport aux autres systèmes de stockage. Plusieurs travaux réalisés ces dernières années ont porté sur l'élaboration et l'optimisation d'un système hybride éolien-diesel avec stockage par air comprimé (SHEDAC) [3] [25] [40] [41] [42].

1.3 ÉTAT DE L'ART SUR LA TECHNOLOGIE SHEDAC

1.3.1. Catégorisation de la technologie SHEDAC

Afin de mieux illustrer les particularités de la technologie SHEDAC, il est nécessaire d'introduire différentes notions propres aux systèmes hybrides telles que le taux de pénétration en énergie renouvelable, ici l'éolien, par rapport aux besoins du système. En effet, les systèmes comme le SHEDAC peuvent se différencier en fonction du taux de pénétration en puissance ou en énergie éolienne [43]. Ainsi, le taux de pénétration en puissance éolienne (TPP) maximal d'un système est défini comme le rapport entre la puissance maximale que peut produire le parc éolien et la puissance maximale de la charge. Le TPP se calcule comme suit :

$$TPP = \frac{P_{éolienne,max}}{P_{charge,max}}$$

De la même façon, le taux de pénétration en énergie éolienne (TPE) est défini comme le rapport entre l'énergie éolienne annuelle et l'énergie consommée annuellement par la charge, soit :

$$TPE = \frac{E_{éolienne,max}}{E_{charge,max}}$$

Pour un site donné, le TPP dépend, donc, du nombre et de la puissance unitaire des éoliennes installées alors que le TPE dépend du TPP ainsi que de la vitesse et de la fréquence du vent sur le site. À partir de ces informations, il serait, alors, possible de définir les classes et les modes opératoires du SHEDAC comme suit [9] :

a) *À faible pénétration en énergie éolienne :* cela concerne les systèmes dont le TPP est compris entre 5 et 50% et le TPE est inférieur à 20%. Dans ce cas-là, la ressource éolienne permet juste de diminuer légèrement l'utilisation des génératrices diesel, mais celles-ci restent, bien souvent, toujours en fonctionnement.

b) *À moyenne pénétration en énergie éolienne :* cela concerne les systèmes dont le TPP est compris entre 50% et 100% et le TPE est compris entre 20% et 40%. Bien que les génératrices restent la plupart du temps en fonctionnement, la part d'énergie éolienne devient plus importante grâce au système de stockage qui peut être utilisé en cas de surproduction des éoliennes.

c) *À haute pénétration en énergie éolienne :* cela concerne les systèmes dont le TPP est compris entre 100% et 400% et le TPE est compris entre 40% et 100%. Dans ce cas-là, dès lors que la vitesse de vent le permet, la production éolienne peut prendre le dessus sur les génératrices diesel, jusqu'à leur arrêt. Une gestion complexe est nécessaire afin d'anticiper les variations brusques de la vitesse de vent, la dissipation d'une surproduction éventuelle (en cas de forts vents), et la mise en marche/arrêt des génératrices si nécessaire.

De manière générale, la part d'utilisation des génératrices diesel et des éoliennes en fonction de la vitesse de vent peut être représentée comme suit [44] :

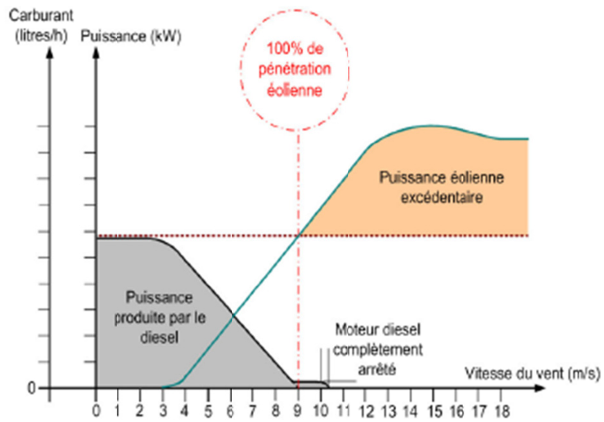

Figure 1.2: Variation de la part d'utilisation des génératrices diesel et des éoliennes en fonction de la vitesse du vent [1]

1.3.2. Travaux et études réalisés sur le SHEDAC

Plusieurs études sur le SHEDAC ont démontré l'efficacité d'un tel système [7] [19] [27] [31] [30] [36]. Dans chaque cas, l'utilisation d'un système hybride éolien-diesel avec stockage par air comprimé permet de réduire de façon considérable l'usage des génératrices et, par conséquent, de diminuer la consommation en carburant diesel.

De plus, à travers les travaux de recherche sur cette technologie, il est intéressant d'étudier la gestion des flux énergétiques. En effet, la technologie de stockage nécessite un contrôle de la puissance entrante, et, d'autre part, l'utilisation de la réserve d'air peut se faire de différentes façons selon la disponibilité et le besoin. Actuellement, on dénombre quelques travaux qui ont déjà étudié les différentes stratégies d'opération pour un SHEDAC [15] [31] [43] [45].

À la suite des travaux de recherche effectués, un banc d'essai pour valider en opération réelle un tel système est devenu nécessaire. Le TechnoCentre éolien, situé à Gaspé au Québec, a ainsi mis en place l'une des premières installations qui permet d'étudier de façon réelle le comportement d'un SHEDAC [46]. La figure suivante illustre le micro réseau mis en place par le TechnoCentre, permettant l'utilisation de la technologie SHEDAC.

Figure 1.3: Photo du micro réseau réalisé au TechnoCentre Éolien [46]

1.3.3. Types de SHEDAC

La technologie SHEDAC vient sous différentes formes selon la fonction et l'application. En effet, chaque forme est composée de sous-systèmes uniques et différents, et à sa propre méthode de gestion. Les deux formes qui seront présentées sont des systèmes à petite échelle et à moyenne échelle [3].

a) *SHEDAC à petite échelle :*

L'utilisation d'un tel système hybride est proposée pour des applications à petite échelle comme des stations de télécommunication ou des petites sites isolés déjà alimentés par des génératrices diesel [47]. La technologie consiste en l'utilisation d'une petite centrale éolienne comme source d'appoint couplée à un moteur d'air comprimé équipé de deux machines (pneumatique et électrique). Le principe de fonctionnement de ce système est alors le suivant : lorsque le TPP>1, l'énergie éolienne excédentaire est utilisée par un alternateur permettant d'entraîner le compresseur afin de recharger les réservoirs d'air comprimé. Si l'énergie éolienne est insuffisante (TPP<1), l'air comprimé est alors détendu dans la machine pneumatique, entraînant l'alternateur pour fournir de l'électricité. Dans de telles configurations, la génératrice diesel n'est utilisée que si la centrale éolienne et le dispositif de stockage ne peuvent assurer les besoins énergétiques. Le schéma de principe de ce système est présenté dans la figure ci-dessous. Il est important de souligner que ce genre d'hybridation permet de diminuer la consommation en carburant et d'éviter le démarrage intermittent des génératrices diesel, permettant ainsi de diminuer leur usure ainsi que les frais d'entretien [3] [47].

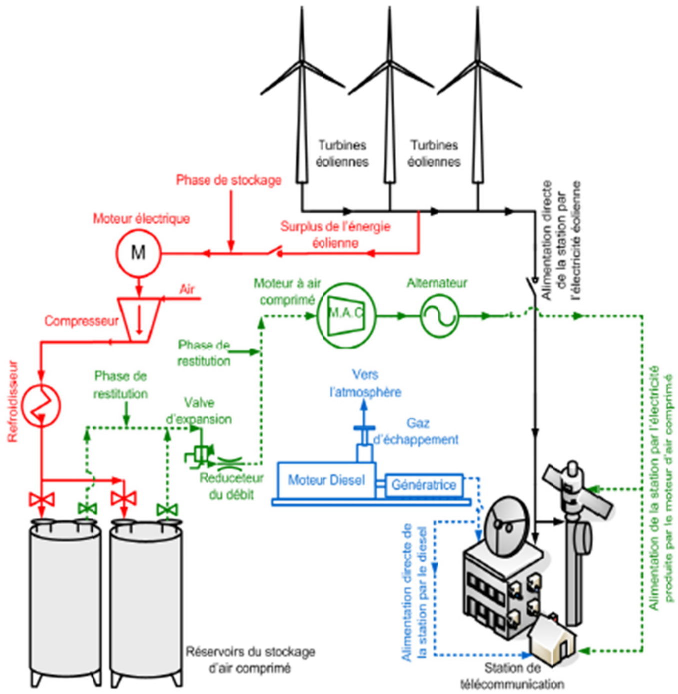

Figure 1.4: Schéma d'une installation d'un SHEDAC à petite échelle [3]

b) <u>SHEDAC à moyenne échelle :</u>

Ce genre d'hybridation est utilisé dans le cas des applications isolées de moyenne et grande échelle quand l'utilisation de génératrices diesel est inévitable [3]. La situation géographique impose des coûts prohibitifs pour le transport du carburant. Comme précédemment, le principe de cette technologie consiste à mettre en œuvre une centrale éolienne ainsi qu'un système de stockage par air comprimé. Cependant, l'air comprimé stocké ne sera pas utilisé ici comme source énergétique directe, mais plutôt pour améliorer les performances des génératrices diesel, tout en augmentant le taux de pénétration de l'énergie éolienne. Il s'agit, alors, de la « suralimentation supplémentaire » des moteurs diesel [3] [29] [43] [44].

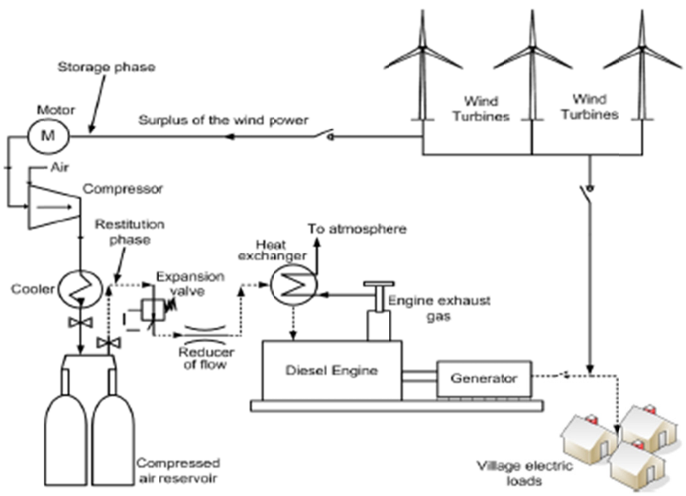

Figure 1.5: Schéma d'une installation d'un SHEDAC à moyenne échelle [3]

Le procédé de suralimentation consiste à élever la masse volumique de l'air à l'admission des moteurs pour en augmenter leur puissance spécifique (puissance par unité de cylindrée) [48]. Ainsi, lorsque le TPP>1, le surplus de l'énergie éolienne est utilisé pour comprimer l'air qui est ensuite stocké. Au moment où c'est nécessaire, l'air comprimé sert à suralimenter le moteur diesel afin d'en augmenter sa puissance produite. Cela permet de diminuer la consommation en combustible et l'usure des moteurs. Différentes études et publications ont ainsi été réalisées dans le but de trouver la meilleure manière de suralimenter les génératrices [3]. De ces travaux ont été déduites les différentes alternatives de suralimentation suivantes :

- Utilisation d'une turbine en série sur l'axe du turbocompresseur ;
- Double étage de suralimentation ;
- Admission en amont du compresseur ;
- Admission directe dans le moteur (Figure 1.6) ;
- Suralimentation Hyperbar ;

- Suralimentation avec un cycle de Lenoir pressurisé ;
- Suralimentation avec downsizing.

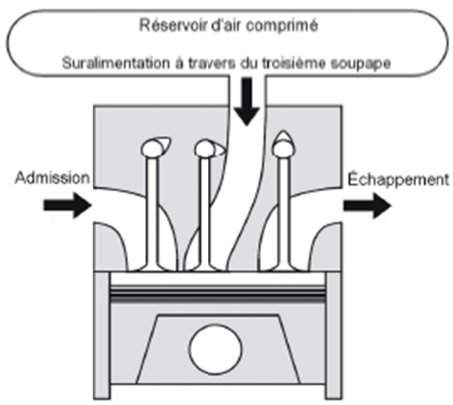

Figure 1.6: Schéma de principe - admission directe dans le moteur [3]

À travers ces solutions, il a été démontré que l'utilisation d'un moteur avec de l'air comprimé ne s'est pas limitée à la suralimentation puisqu'il a été prouvé que l'usage en mode pneumatique s'avère être une solution pertinente.

1.4 OBJECTIFS ET METHODOLOGIE DU TRAVAIL

1.4.1 Objectifs du projet de recherche global et de ce mémoire

Le présent mémoire porte sur l'étude de faisabilité d'un système hybride éolien-diesel avec stockage par air comprimé (SHEDAC). Ces travaux ont été ensuite appliqués pour une situation concrète d'un SHEDAC installé dans un site isolé situé dans le Nord-du-Québec.

L'objectif principal du présent projet a été de concevoir et valider un outil d'aide à la décision pour le SHEDAC afin de l'utiliser pour l'analyse de rentabilité financière. Cet outil a été utilisé pour l'étude de l'implantation d'un SHEDAC dans un site éloigné dans le Nord-du-Québec.

Les objectifs principaux du projet sont les suivants :

a) Concevoir un logiciel d'analyse financière d'un SHEDAC qui permet une étude économique pour des nombreuses configurations possibles. Cette étude est basée sur l'analyse des coûts et des revenus, des coûts des équipements (éolienne, moteur diesel, système de stockage d'air). Elle est complétée par une analyse de sensibilité aux différents paramètres, une analyse des risques et des émissions des gaz à effet de serre (GES). Une validation des simulations est réalisée par comparaison avec des outils similaires.
b) Utiliser l'outil développé pour l'application sur le cas d'étude du projet dans le Nord-du-Québec. Une analyse financière est menée pour déterminer la rentabilité du système dans ce contexte.

1.4.2 Méthodologie

La méthodologie définie pour la réalisation des objectifs présentés précédemment est établie en plusieurs étapes et sous étapes à respecter :

A. Développement d'un outil pour l'analyse de rentabilité, de sensibilité, de risque et d'étude d'impact environnemental d'un système hybride éolien-diesel avec stockage par air comprimé :

    a) État de l'art des différents logiciels existants pour l'analyse de rentabilité des systèmes hybrides afin d'attester la nécessité de développer un outil pour l'analyse de rentabilité d'un SHEDAC ;

    b) Recherche des modèles existants pour les analyses de rentabilité, de sensibilité, de risque et d'étude d'impact environnemental. Les modèles déjà utilisés dans les logiciels existants seront privilégiés pour s'assurer d'obtenir des modélisations appropriées ;

c) Modélisation et programmation de l'outil pour le SHEDAC.

d) Validation de la véracité des résultats proposés par le logiciel. En utilisant des outils dont la fiabilité a déjà été acceptée par la communauté scientifique, il s'agira de valider la pertinence des modèles choisis et des résultats obtenus.

B. L'analyse de rentabilité, de sensibilité, de risque et d'étude d'impact environnemental d'un SHEDAC pour une application en site isolé, à l'aide du logiciel développé :

a) Utiliser les résultats de l'analyse technique produite par le logiciel [28] du site étudié afin de dégager l'investissement initial, le coût de remplacement et d'exploitation, et le coût de la maintenance pour entamer l'analyse financière.

b) Se servir des résultats l'analyse financière pour mener une analyse de sensibilité et de risque.

c) Utiliser les résultats de l'analyse technique pour mener une étude d'impact environnemental.

1.5 STRUCTURE DU MEMOIRE

Le présent mémoire est produit par articles. Ainsi, les différents articles soumis ou publiés dans des journaux scientifiques avec comités de lecture constituent les chapitres du mémoire.

Le premier article présente le développement d'un logiciel dédié à l'étude de faisabilité d'un système éolien-diesel avec stockage d'air comprimé. Cette étude est basée sur l'analyse des coûts et des revenus, des coûts des équipements (éolienne, moteur diesel, système de stockage d'air). Elle est complétée par une analyse de sensibilité aux différents paramètres, une analyse des risques et des émissions des gaz à effet de serre (GES).

Le deuxième article est une application de ce logiciel pour l'installation d'un système SHEDAC au camp minier Esker au Québec en remplacement des sources actuelles de production d'énergie. L'utilisation du stockage d'air comprimé à l'aide d'un système SHEDAC est le plus rentable par rapport à l'utilisation de l'énergie éolienne seule ou d'une centrale thermique au diesel seule ou des deux combinées. Avec une valeur actuelle nette et un taux de rendement interne plus élevés, cette solution permet d'obtenir le plus bas coût de l'énergie pour cette région éloignée.

CHAPITRE 2
MODÈLE NUMÉRIQUE POUR L'ANALYSE ENVIRONNEMENTALE, FINANCIÈRE ET DE RISQUE D'UN SYSTÈME HYBRIDE ÉOLIEN-DIESEL AVEC STOCKAGE D'AIR COMPRIMÉ

2.1 RESUME

Dans cet article, est présentée un logiciel destiné à la modélisation et l'analyse financière, analyse de risque et écologique d'un système hybride éolien-diesel avec stockage par air comprimé. Plus précisément, cet outil permet l'étude de rentabilité d'un tel système par rapport à des systèmes conventionnels comme l'usage de génératrices diesel seules. Pour ce faire, ont été modélisés, et implantés dans la programmation du logiciel, les différents types d'analyse reliés au SHEDAC, à savoir : l'analyse financière, analyse de sensibilité, de risque et l'étude d'impact écologique.

Dans le but de valider la pertinence des résultats obtenus avec le logiciel, des comparaisons avec des logiciels déjà existants et fiables, HOMER© et RETScreen, ont été réalisées sur une étude de cas appliquée au camp minier d'Esker. Avec un écart de résultats inférieur à 10% en moyenne, il a ainsi été prouvé que l'outil mis en place est parfaitement pertinent pour l'analyse de rentabilité été écologique de systèmes hybrides en énergie.

Il y est présenté, ensuite, une étude de cas afin d'évaluer les résultats d'un système « idéal » pour l'étude de cas traitée dans l'article. Le système « idéal » est dimensionné en supposant qu'il n'y a aucune contrainte au niveau du stockage, c'est-à-dire qu'il n'y pas de pertes liées au processus de stockage et qu'il est possible de stocker de l'air indéfiniment. Ainsi, grâce à la configuration du SHEDAC établie, les résultats présentent une économie de carburant possible de 25,6 % (en basse pénétration éolienne) par rapport à un système composé uniquement de génératrices. Toutefois la rentabilité financière du SHEDAC pour un projet de petite envergure est légèrement plus faible que celle de l'utilisation des énergies fossiles. Ceci est largement dû à l'investissement initial qui est très élevé.

Pour ces raisons, le logiciel ainsi que les résultats obtenus pour une étude de cas précise ont permis de valider la rentabilité et l'impact écologique d'un SHEDAC en site isolé, et de proposer un nouvel outil universel pour la réalisation d'une telle étude. Le deuxième article, présenté dans le chapitre suivant, permet alors de mettre à profit l'utilisation du logiciel développé ici, afin de réaliser afin de réaliser une étude complète ainsi qu'une optimisation de rentabilité sur le cas du camp Esker.

COMPUTER MODEL FOR ENVIRONMENTAL, FINANCIAL AND RISK ANALYSIS OF A HYBRID WIND-DIESEL SYSTEM WITH CAES

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Nomenclature:

- WPPR : Wind Power Penetration Rate
- WEPR : Wind Energy Penetration Rate
- WDCAS : Wind–Diesel-Compressed Air Storage
- CAES : Compressed Air Energy Storage
- GHG : Green House Gas
- WDS: Wind Diesel hybrid System
- GUI: Graphical User Interface
- IRR: Internal Rate of Return
- NPV: Net Present Value
- NPC: Net Present Cost

- IP: Index of Profitability
- COE: Cost of Energy
- λ : Stoichiometric air/fuel ratio
- η_e : Electric efficiency of the wind turbine
- η_{i_DE} : Indicated efficiency of the engine
- η_{p_C} : Polytropic efficiency of the compressor
- η_{tr} : Transmission efficiency between the engine and the compressor
- η_{v_DE} : Volumetric efficiency of the engine
- π_C : Total compression ratio
- π_{i_C} : Compression ratio for each stage
- ρ_a : Air density
- A : Fuel consumption parameter
- B : Fuel consumption parameter
- c : Scale parameter (Weibull distribution)
- C_{P_WT} : Power coefficient
- E_{an_CH} : Annual energy consumption of the charge
- $E_{\bar{v}_w}$: Annual energy production of the wind turbine
- $f(v_w)$: Weibull density probability function
- h_{WT} : Wind turbine hub height

- h_0 : Reference height
- k : Shape parameter (Weibull distribution)
- $\dot{m}_c$: Compressed air mass flow rate (from the compressor)
- $\dot{m}_{f\_DE}$: Fuel mass flow rate injected in cylinders
- $\dot{m}_{in\_DE}$: Air mass flow rate entering the engine
- $\dot{m}_u$: Capacity of a storage unit
- n_c : Polytropic index
- N_c : Number of compressor stages
- N_{max_unit} : Number of maximum storage units
- NB_{WT} : Number of wind turbines
- ND_{auto} : Number of days of autonomy
- p_a : Inlet atmospheric pressure of the compressor
- p_{ou_C} : Outlet pressure of the compressor
- p_{in_DE} : Inlet pressure of the diesel engine
- p_{st} : Storage pressure
- P_C : Power of the multi-stage compressor
- P_{C_1} : Power of the single-stage compressor
- P_{CH} : Power of the charge
- P_{CH_ave} : Average power of the charge

- P_{DE} : Power of the diesel engine
- P_{EM} : Minimal power required to start the electric motor of the compressor
- P_{EX_WT} : Excess wind power
- P_{max_CH} : Maximum power of the charge
- P_{max_WT} : Maximum wind turbine power
- P_{nDE} : Nominal diesel engine power
- $P_{WT}(v_w)$: Wind turbine power
- $P_{WT\_a}(v_w)$: Wind power
- PCI : Indicated lower calorific value of the fuel
- R : Perfect gas constant for the air
- S_{WT} : Swept area
- t_{step} : Time step
- t_{total} : Duration of the simulation
- T_{st} : Storage temperature
- V_{st} : Total volume of the storage
- v_w : Wind speed
- v_{0_w}: Wind speed at the reference height
- α : Wind shear coefficient

Abstract:

A hybrid energy system combines two or more electricity generators using renewable energy resources and/or fossil fuel. Such systems are used mostly to supply electricity to remote areas. To achieve higher penetration of wind energy and an optimal operation of diesel generators one of the best solutions is to use Compressed Air Energy Storage (CAES). The resulting hybrid system is hence called *Wind–Diesel with Compressed Air Storage (WDCAS)*. The WDCAS is characterized by technical, economic and environmental parameters such as the wind power penetration rate, cost of energy, the renewable energy fraction, etc. In a previous publication [1] the authors presented a software for the design and technical analysis of WDCAS. In this current paper the authors develop a model and associated software for the economic analysis and risk assessment of the WDCAS. The economic analysis incorporates the financial, sensitivity and risk analysis. The model has been validated by comparing the results for a wind-diesel case study with those of HOMER and RETScreen software. The impact on economic and financial performances of adding CAES and use a complete WDCAS system has then been explored.

Introduction

Most of the sites in remote areas rely on diesel generators to produce electricity [2], which are characterized by high production costs and are responsible for greenhouse gas (GHG) emissions [36]. The exploitation of diesel engines in these remote areas is not only sensible to fuel prices fluctuations but preponderantly due to fuel transportation costs [4] [38]. Therefore, the use of wind energy or other renewable resources (solar, hydro) when locally available is an effective solution to reduce production costs and GHG emissions. Hybrid systems that combine solar and wind energy with diesel generators and energy storage have been implemented and studied [6]. In remote areas, the power production should permanently balance the charge so that the isolated electrical grid remains stable. For wind-diesel systems for instance, when the power produced by the wind turbines is lower than the charge, the balance should be provided by diesel generators. High penetration of wind power occurs when the installed power of wind turbines is higher than the maximum charge. Therefore, sometimes the wind power will be in excess and the use of energy storage is suitable. Among different solutions, the use of Compressed Air Energy Storage (CAES) will optimize the operation of diesel engines by supplying as much air as required by an optimal air/fuel ratio. The system, called Wind-Diesel System with Compressed Air Storage (WDCAS) has significant advantages as described in detail in previous work [1] [40] [41] [42] [43] [11] [45]. A higher penetration of wind energy results in longer periods when there is an excess of wind energy over the charge. During these periods, the surplus of wind energy is converted into compressed air. When wind energy is insufficient to provide the charge, the diesel generators are used. With higher wind power penetration rate (WPPR), most of the time, these diesel generators are operating at lower than nominal regimes and use the stored compressed air to operate at maximum efficiency, i.e. optimal air/fuel ratio [46] [14].

The technical and economic analysis tools commonly used for the design and the optimization of hybrid systems are considering a multitude of production sources (grid, diesel, wind, solar, biomass, etc.) and storage capabilities (batteries, hydrogen) but none of them uses compressed air storage as it changes the operation characteristics of diesel engines. For this reason, a new software has been developed to design and the technical performance of a WDCAS system [1]. In this paper, the models and algorithms for the economic and risk analysis of WDCAS system are build. These decision tools are inspired by those available in other renewable energy software such as HOMER [15] or RETScreen software [16] developed by Natural Resources Canada. They provide economic and risk analysis for systems using only renewable energy sources while HOMER compares different hybrid systems based on a global parameter, the cost of energy.

In this paper the most important characteristics of WDCAS technology and the decision tools available in the existing software HOMER and RETScreen for economic, environmental and risk assessment are briefly illustrated. Then, the paper presents the new environmental, economic and risk evaluation tools for WDCAS systems along with a case study for validation.

Wind Diesel with Compressed Air Storage (WDCAS) System

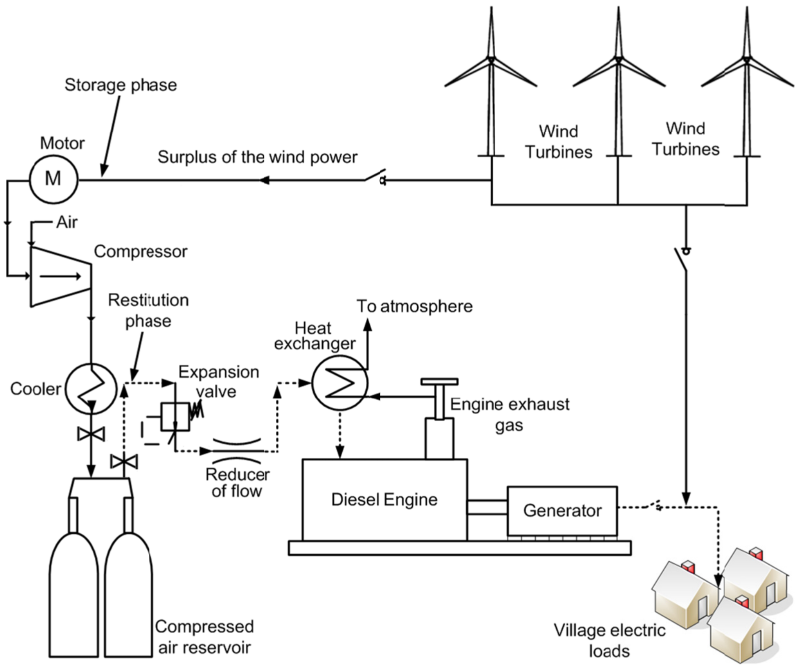

Figure 7: WDCAS Technology representation [1]

The WDCAS stands as one of the best solutions for diesel hybridization with renewable energies as fuel consumption is reduced both by the use of renewable energy and by the optimization of the diesel engine. The cost, simplicity, lifespan, contribution to reducing fuel consumption and greenhouse gas (GHG) emissions are the advantages of this young technology that makes it appropriate for wind-diesel hybridization. The main components of a WDCAS are the initial energy source (diesel), renewable energy source (wind) and the compression and storage system (compressor and reservoir). Other subsystems must be added to ensure the management of energy flows and correct operation of the hybrid system as: the expander, dumping loads, automatic control systems [17] [46] [51] [52] [53] [21].

The principle of WDCAS operation is generally the same, although it may vary depending on the size of the installation and the wind power penetration rate. Diesel engines and wind turbines contribute to supplying the load. If wind power is in excess (strong wind regimes), it is used to compress the air which is then stored in a tank that can be natural or superficial. During low winds, this air is injected into the engines that operate in different modes: supercharged, hybrid or pneumatic [22]. Regardless of the mode, the stored compressed air serves to improve engine performance and reduce fuel consumption.

The performances of a WDCAS system have been determined at specific regimes and implementation scenarios (high or low penetration, high or low storage, etc.).

A high penetration system is used when the installed wind power is larger than the maximum charge [56] [57]. If installed wind power is such that diesels have to run continuously, the wind-diesel hybrid system is classified as low or medium wind penetration depending on the ratio of installed wind power over primary electrical load. Low penetration systems are considered those with less than 50% peak instantaneous wind penetration while medium penetration systems are those for which this value is between 50% and 100%. Low and medium penetration systems are a mature technology. High penetration systems (more than 100% peak instantaneous penetration), however, still face technical problems, especially when installed to operate in a diesel-off mode [25]. In the existing high penetration wind-diesel systems, the wind energy in excess is stored either as thermal energy (hot water) or in batteries which are expensive, difficult to recycle, a source of pollution (lead-acid) and limited in power and lifecycle [59] [27]. The storage of compressed air has the advantages to be easily adaptable to the hybrid system, to improve the efficiency of the diesel operation at lower regimes, to be available in real time and offer smooth power fluctuations.

Software Model of the Wind-Diesel System with Compressed Air Storage (WDCAS)

The characteristics of the software and the physical models used for each subsystem are presented in this section.

Basic parameters:

Simulation time and time step:

The user can choose the duration of the analysis (t_{total}) and the time step (t_{step}) for the simulation. This time step time is the same for the load and meteorological data. The default value is $t_{step}=1h$.

Energy balance:

The software uses the following energy balance equation at every time step over the complete duration of the simulation:

$$Load = Wind\ Turbine\ Power + Diesel\ Generator\ Power - Power\ Compressed\ Air\ Storage \tag{1}$$

For each time step, diesel generator power and/or the power used for compressed air storage are adjusted to estimated load and available wind power. Function of the load, the wind resource and the storage level, the power terms are calculated.

Subsystems modeling:

Load:

The software does not use any specific model for the load; the user should provide a table with the hourly data according to each specific project.

Wind Turbine Power:

The wind turbine instantaneous power (energy if we consider it over one time step) is determined by the average wind speed at that particular moment (or time step) and the type of wind turbine.

The wind turbine (WT) power curve represents the variation of the power output with the wind speed $P_{WT}(v_w)$ and is provided by each manufacturer. Energy production over a given time period will consider both wind turbine power curve and wind speed distribution. As an example, the annual energy production is:

$$E_{\bar{v}_w} = 8760 \sum_{v_w=0}^{v_w=25} P_{WT}(v_w) f(v_w) \tag{2}$$

with Weibull distribution defined as:

$$f(v_w) = \left(\frac{k}{c}\right)\left(\frac{v_w}{c}\right)^{k-1} \exp\left[-\left(\frac{v_w}{c}\right)^k\right] \tag{3}$$

Weibull distribution represents the probability to have a certain wind speed. Its parameters, c (scale factor) and k (shape factor) are characteristics of the site and should be provided by the user. If only average wind speed is known at the site, then k is assumed equal to 2 (k=2, Rayleigh distribution) and c is computed.

One of the main characteristics of a hybrid system is the wind power penetration rate (WPPR) defined as the ratio of installed wind power capacity to maximum load:

$$WPPR = \frac{P_{\max\_WT}}{P_{\max\_Load}} \tag{4}$$

Similarly, the wind energy penetration rate (WEPR) represents the share of wind energy in total energy over a given period of time, generally one year:

$$WEPR = \frac{E_{\bar{v}_w}}{E_{Load}} \quad (5)$$

These characteristics are important as different system topologies, operation strategies and economic parameters are specific to each low, medium or high penetration level of wind energy. In the software, the user should define the desired WPPR level of the system. According to this value, the software determines the number of wind turbines needed:

$$NB_{WT} = \frac{P_{\max\_Load} * WPPR}{P_{WT}(v_w)} \quad (6)$$

Based on Weibull distribution characteristics, the software will generate wind speed values over the entire period of analysis. The generated wind power at each time step is then computed based on the number and power curve of the wind turbines.

<u>Diesel Generator Power:</u>

The WDCAS simulation software allows one or more diesel generators operating in "normal mode" (without compressed air for overcharging) and/or supercharged with compressed air. In this context, the computational models described in references [27] [61] [62] have been used. For normal operation, fuel consumption is determined based on the diesel required power and its technical characteristics using:

$$\dot{m}_{f\_DE} = A \cdot P_{DE} - B \quad (7)$$

where A and B are technical parameters of the diesel generator used. The indicated efficiency is determined as:

$$\eta_{i\_DE} = \frac{P_{DE}}{PCI * \dot{m}_{f\_DE}} \quad (8)$$

In supercharged mode, the stored compressed air is used such as to maintain an air/fuel ratio (λ) value resulting in optimal diesel efficiency. Air/fuel (λ) ratio is defined as:

$$\lambda = \frac{\dot{m}_{in\_DE}}{\dot{m}_{f\_DE}} \quad (9)$$

Previous studies have shown that maximum efficiency of the diesel engine ($\eta_{i_{DE}} \cong 56\%$) is reached for an air/fuel ratio of $\lambda \cong 53$ [61]. Therefore, the software will consider this optimal ratio for all overcharged operation regimes. The fuel rate and compressed air flow rate required to supercharge the diesel are determined from the following equation, where we consider $\eta_{i_{DE}}$=56% :

$$P_{DE} = PCI * \eta_{i\_DE} * \dot{m}_{f\_DE} = PCI * \eta_{i\_DE} * \frac{\dot{m}_{in\_DE}}{\lambda} \quad (10)$$

Compressed air storage

The compressor type determines how the excess of wind energy is used over the charge resulting from equation (1) and the size of the storage tank. Subsystem modeling uses physical parameters related to air compression phenomena. The software doesn't have predefined compressors and the user should configure them according to specific situation.

The relation between power and compression ratio of a single-stage polytropic compressor [61] is defined by:

$$P_{C\_1} = \frac{n_C}{n_C - 1} * \dot{m}_C * R * T_{st} * \left[\left(\frac{p_{ou\_C}}{p_a} \right)^{\frac{n_C - 1}{n_C}} - 1 \right] * \frac{1}{\eta_{p\_C}} \tag{11}$$

The most convenient solution to increase the compression ratio is to combine several single-stage compressors or directly use a multi-stage compressor. The software is considering identical compression ratio for each stage of the compressor, as follows:

$$\pi_{i\_C} = \frac{p_1}{p_a} = \frac{p_2}{p_1} = \frac{p_2}{p_3} = \cdots = \frac{p_{N_C}\,(=p_{ou\_C})}{p_{N_C - 1}} \tag{12}$$

The resulting compression ratio for the whole compressor, defined as the ratio between the outlet and atmospheric pressure is then:

$$\pi_C = \frac{p_{ou\_c}}{p_a} = \left(\pi_{i\_C} \right)^{N_c} \tag{13}$$

The software considers that the outlet pressure is identical to the storage pressure and its value is provided as an input data by the user. The relation between the multi-stage compressor power and compressed air mass flow rate becomes:

$$P_C = \frac{n_C N_C}{n_C - 1} * \dot{m}_C * R * T_{st} * \left[\left(\frac{p_{ou\_C}}{p_a} \right)^{\frac{n_C - 1}{n_C N_C}} - 1 \right] * \frac{1}{\eta_{p\_C}} \tag{14}$$

In the meantime, this compressor power is equal to wind power surplus adjusted with electric motor and transmission efficiency:

$$P_C = P_{EX\_WT} \cdot \eta_{tr} \cdot \eta_e = (P_{WT} - P_{CH}) \cdot \eta_{tr} \cdot \eta_e \tag{15}$$

Storage tank

The key parameter of this subsystem is the storage unit which represents the quantity of compressed air coming out from the tank that is required to supercharge the diesel such as to deliver a power equivalent to the average charge, during one time step (generally one hour). The assumption of an optimal supercharging of the diesel is formulated. Thus, the maximum efficiency of the diesel engine ($\eta_{i_{DE}} \cong 56\%$), reached for an air/fuel ratio of □≅53 are used to determine the storage unit as follows:

$$\dot{m}_u = \frac{\lambda * P_{CH\_ave}}{\eta_{i\_DE} * PCI} \quad (16)$$

The user should provide the number of days of autonomy ND_{auto} during which the system should provide energy without wind, by using only the supercharged diesel generator. As a result, the required number of storage units is:

$$N_{\max\_unit} = ND_{auto} * 24 * 3600 * \frac{t_{step}}{1\ Hour} \quad (17)$$

If the time step is one hour (which is usually the case) the last term in the equation (17) is equal to unity. The volume of the storage tank will be:

$$V_{st} = \frac{N_{max\_unit} * \dot{m}_u * R * T_{st}}{p_{st}} \quad (18)$$

According to each operating scenario, the software determines the required number of diesel generators to operate. If the system operates only with generators, this number is calculated as follows:

$$NB_{DE} = \left|\frac{P_{Load}}{P_{nDE}}\right| + 1 \quad (19)$$

If the system operates with generators and wind turbines, this number is calculated as follows:

$$NB_{DE} = \left|\frac{P_{Load} - P_{WT}}{P_{nDE}}\right| + 1 \quad (20)$$

Financial Background:

In any financial analysis, there is a series of financial parameters used to manage a project; this section discusses the ones calculated by the WDCAS software.

Net Present Value

In finance, the Net Present Value (NPV) is defined as the sum of the discounted values of costs and benefits over a period of time. Time value of money dictates that time has an impact on the value of cash flows, due to inflation and financial risk.

The way NPV [63] is computed is:

$$NPV = \sum_{t=1}^{n} \frac{A_t}{(1+r)^t} - I \quad (21)$$

Where

- A_t is the cash flow during year *t*
- r is the discount rate
- I is the initial capital or the initial investment
- n is the duration of the project in years

Internal rate of return

The Internal Rate of Return (IRR) is a rate of return used to measure and compare the profitability of investments. The term internal refers to the fact that its calculation does not incorporate environmental factors (e.g., the interest rate or inflation). It is the discount rate where the project is no longer profitable; in other terms it is rate where the discounted benefits and the discounted costs are equal. A more concise way to view the IRR, it is the discount rate that cancels the NPV.

The the IRR [31] is calculated such that:

$$NPV_{IRR} = 0 \tag{22}$$

$$\sum_{t=1}^{n} \frac{A_t}{(1+IRR)^t} - I = 0 \tag{23}$$

According to this formula, the IRR is calculated by iteration of the left hand side until the desired precision is reached, a value usually close to zero.

Payback Period

The Payback Period (PP) refers to the period of time required to recover the investment without considering the value of money over time:

$$PP = \frac{I}{A} \tag{24}$$

In the Discounted Payback Period (DPP), the discount rate is introduced to correct each annual cash flow at its present value, as in NPV formula.

Profitability index

The profitability index (PI) is the ratio of payoff to investment of a proposed project. In other words, it is the amount of value created per unit of investment, thus a useful tool for ranking projects. The formula for the profitability index [32] is:

$$PI = \frac{\sum_{t=1}^{n} \frac{A_t}{(1+r)^t}}{I} = \frac{NPV}{I} + 1 \tag{25}$$

Cost of energy

The Cost Of Energy (COE) is the equivalent cost of a kWh of electricity generated from a specific source to break even over the lifetime of the project. It is a financial tool to evaluate the cost of the energy-generating system including all the discounted costs over its lifetime.

The discounted costs in a project are also called the net present cost (NPC), it includes initial investment, operations and maintenance, cost of fuel, cost of capital, and is very useful in calculating the costs of generation from different sources.

Since the principle of time value applies also to energy, the energy produced at a certain point in time has more value than if produced later; this is the reason for computing the COE as the discounted costs divided by the discounted energy. We typically use the same discount rate for the cost and the energy, thus the COE [33] is calculated as follows:

$$COE = \frac{NPC}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} = \frac{\sum_{t=1}^{n}\frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \tag{26}$$

where

- C_t is the outflow (sum of all costs) at year t
- r is the discount rate
- E_t is the energy generated at year t

Sensitivity analysis:

In this type of analysis, the impact of a fixed variation in the parameters affecting the financial indicators is measured [34]. These parameters are the initial investment (I), the duration of the project, the number of years (n), the cash flow (C) and the discount rate (r). The financial indicators are the ones indicated, the *NPV*, *IRR*, *PP* and *PI*.

Each financial indicator F is a function of the vector of parameters $X = (x_1, x_2, x_3, x_4)$ in the form $F(X)$.

The sensitivity analysis can be one or two dimensional, i.e. based on the influence of a single parameter or two parameters simultaneously. This is discussed in the following paragraphs.

For one dimensional analysis, the software creates a vector A composed of 5 items that reflects the impact of each term x_i of X on F, according to a general variation v. The impact is considered from a variation of $\frac{-v}{2}$, $\frac{-v}{4}$, 0, $\frac{v}{4}$, and $\frac{v}{2}$. This variation v is translated as $r_i = \frac{i-3}{4}v$ where i varies from 1 to 5. Mathematically, we have:

$$A_i = F(x_i(1 + r_i), x_j, x_p, x_q) \quad (27)$$

where i varies from 1 to 5 with the other parameters x_j, x_p, x_q fixed. The impact of each variation of x_i on F is expressed in the form of the following vector A:

Variation	Result
$\frac{-v}{2}$	$F(x_i\left(1+\frac{-v}{2}\right), x_j, x_p, x_q)$
$\frac{-v}{4}$	$F(x_i\left(1+\frac{-v}{4}\right), x_j, x_p, x_q)$
0	$F(x_i, x_j, x_p, x_q)$
$\frac{v}{4}$	$F(x_i\left(1+\frac{v}{4}\right), x_j, x_p, x_q)$
$\frac{v}{2}$	$F(x_i\left(1+\frac{v}{2}\right), x_j, x_p, x_q)$

For two dimensional analysis, a 5 by 5 matrix B is created. It reflects the combined impact of the variation of each pair x_i and x_j on F. The impact is represented, as before, considering a variation of $\frac{-v}{2}$,$\frac{-v}{4}$, 0, $\frac{v}{4}$, and $\frac{v}{2}$ translated as $r_i = \frac{i-3}{4}v$ (i varies from 1 to 5) for two parameters, simultaneously. Thus, the elements of the matrix B, are :

$$B_{ij} = F(x_i(1 + r_i), x_j(1 + r_j), x_p, x_q) \quad (28)$$

i, j are indices varying independently from 1 to 5 and $x_p, x_q$are fixed. The impact is expressed in the form of matrix B as follows:

Variation					
$\frac{-v}{2}$	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}
$\frac{-v}{4}$	B_{21}	B_{22}	B_{32}	B_{42}	B_{52}
0	B_{31}	B_{23}	B_{33}	B_{43}	B_{53}

$\frac{v}{4}$	B_{41}	B_{24}	B_{34}	B_{44}	B_{54}
$\frac{v}{2}$	B_{51}	B_{25}	B_{35}	B_{45}	B_{55}

Emissions evaluation

The emission analysis provides the quantity of CO_2 generated by the system [35].

It is calculated using the formula:

$$e_{CO_2} = E_{system}\, f_{CO_2} \tag{29}$$

Where:

- e_{CO_2} is the CO2 emission in kgCO2
- E_{system} is the energy produced by the system in kWh, whether it's diesel alone or WD or WDCAS
- f_{CO_2} is the emission factor in kgCO2/kWh

Risk analysis:

The risk analysis model embedded within the WDCAS software is based on Monte Carlo simulations [35], which is a method that generates values of a financial indicator following a certain probability distribution. This probability distribution has the mean and the standard deviation as entry parameters.

Mathematically, the code generates m numbers (by default *m*=500) according to the normal probability distribution with an average of zero, and standard deviation of 1/3, $m \sim N\left(0, \frac{1}{3}\right)$. The risk of a variation r_i of parameter x_i is considered and then multiplied by the random numbers generated before:

$$R_i = r_i\, m \tag{30}$$

Then, the financial indicator is computed according to the new values of the parameters:

$$F(x_i(1 + R_i), x_j, x_p, x_q) \tag{31}$$

Finally, the frequency of F is plotted according to the range of its values generated by the simulation. The WDCAS software can do Monte Carlo simulation for the four financial parameters, namely NPV, IRR, PI, and the payback.

The risk analysis includes an impact diagram. This feature allows to visually illustrate the impact of a certain parameter for a chosen financial indicator.

The financial indicator is subject to a multi-linear regression using least squared method. The result is

$$\bar{F}(X) = \sum_{i=1}^{4} \alpha_i x_i + \varepsilon \tag{32}$$

where α_i is the slope of each entry, ε is the error due to the regression, x_i the financial parameter and $\bar{F}$ the regressed financial indicator.

Since the impact can be represented by the contribution of each regressed parameter within the total change, it is suitable to say that the impact γ_i is a percentage equal to:

$$\gamma_i = \frac{\alpha_i x_i}{\bar{F}(X)} \tag{33}$$

Since random numbers generate these values (x_i), it is useful to visualize the impact of how a variation in x_i creates a change in $\bar{F}(X)$; in mathematical terms ,the following parameter is required:

$$\beta_i = \frac{\alpha_i \sigma_i}{\sigma_F} \tag{34}$$

where σ_i is the standard deviation of the inputs (x_i) due to Monte Carlo simulations, and σ_F the standard deviation of the result. The β_i is a more accurate measure of the impact since it deals with data resulting from a probability distribution. Ultimately, β_i are plotted to obtain an impact diagram.

A last feature of the risk analysis is the median and confidence interval of the financial indicator of interest. The median is straightforward; it is the median of the 500 Monte Carlo simulations. For the confidence interval, the amount of risk that we are willing to take in the project, call it ξ, is chosen Then, the 500 values from the Monte Carlo simulations are written in an ascending order to give a statistical series. The lower limit of the confidence is chosen to be ξ-th percentile of the series, and the upper limit is $(1 - \xi)$-th percentile. Finally, the confidence interval is between the lower and the upper limit.

As a conclusion, the risk analysis offers a more realistic forecast of financial indicators to help decision making process.

State of the art of hybrid renewable system software

Before presenting the WDCAS software, a brief state of the art of existing design and analysis tools for hybrid energy systems is presented (Table 1) to underline its new features. Most of the existing available software can be applied to the design and analysis of hybrid, wind and solar systems (photovoltaic and thermal) as presented in this chart:

Table 1: List of hybrid renewable design system software

Software	Country	Goals	Technologies of electric production	Technologies of energy storage
HOMER	United States	Technical and economic sizing of hybrid networks with renewable energy	Photovoltaic, wind turbine, hydroelectric, diesel generator, biomass.	Electrochemical cells, flywheel, hydrogen storage.
RETScreen	Canada	Analysis (technical, economic and environmental) of clean energy projects	Photovoltaic, wind turbine, hydroelectric, diesel generator, gas turbine, marine energy, geothermal, biomass.	Thermal storage, fuel cell.
JPElec	France	Simulation and analysis of power grids in steady state	Photovoltaic, wind turbine, hydroelectric, diesel generator.	Electrochemical cells.
Hybrid 2	United States	Technical and economic sizing of hybrid networks with renewable energy	Photovoltaic, wind turbine, diesel generator.	Electrochemical cells.
HySim	United States	Technical and economic analysis of remote rural off grid hybrid system	Photovoltaic, diesel generator.	Electrochemical cells
HySys	Spain	Sizing and long-term analysis of off grid hybrid systems	Photovoltaic, wind turbine, diesel generator.	-
Hybrid Designer	South Africa	Technical and economic sizing of hybrid systems with renewable energy	Photovoltaic, wind turbine, diesel generator.	Electrochemical cells
SOLSIM	Germany	Technical and economic analysis of hybrid systems with renewable energy	Photovoltaic, wind turbine, diesel generator, biomass.	Electrochemical cells
TRNSYS	United States	Simulate transient system behavior	Photovoltaic, wind turbine, diesel generator.	Electrochemical cells

Therefore, multiple software solutions are available for the design and analysis of hybrid energy systems for any location in the world. However, they cannot encompass all available solutions and none of them can be used for hybrid systems with compressed air storage. The software to be used to design such systems requires not only the additional modeling of the compressed air storage itself but also the modification of diesel engine characteristics to account for its overcharge with stored compress air. The WDCAS software presented in this paper completes existing tools for the design and analysis of wind-diesel hybrid systems with compressed-air storage.

In the following section, the features of HOMER and RETScreen software that are used for the validation of WDCAS are outlined.

HOMER:

HOMER (Hybrid Optimization of Multiple Energy Resources) is the most used software for the design and analysis of hybrid renewable energy systems. It is systematically used for building cost effective and reliable micro-grids that combine traditionally generated and renewable power, storage, and load management. The National Renewable Energy Laboratory (NREL) USA has developed HOMER for both on-grid and off-grid systems in 1993 and from its release, it has been used by more than 100,000 users in 193 countries [15]. HOMER is programmed using C++ and uses a GUI (Graphical User Interface) for data and results display. The software uses hourly balance between different power sources and the charge to provide feasibility studies as well as optimization and sensitivity analysis [36]. HOMER considers multiple energy production systems, load demand, resources availability and component costs to generate different feasible configurations sorted by NPC (Net Present Cost). It provides various graphs on electric, economic and ecological results which can be exported. HOMER has been used extensively in literature for hybrid renewable energy system optimization and various case studies.

While HOMER software is the most suitable for the analysis of hybrid systems, particularly wind-diesel, it cannot model at this time compressed air storage or WDCAS systems. The main limitations of using HOMER for the WDCAS study are:

- The software doesn't offer compressed air storage alternative;
- The software do not consider diesel operation characteristics when overcharged with stored compressed air;
- The software doesn't offer risk analysis using Monte Carlo simulations;
- HOMER doesn't take into account possible revenues generated by the renewable energy as carbon credits, it only takes into account its cost.

RETScreen:

RETScreen is a feasibility study software developed by Natural Resources Canada [16] to evaluate the energy production, financial and environmental costs and benefits of different renewable energy projects at any location in the world. The software is programmed using VBA and C# as programming languages. RETScreen was released in 1998 for on-grid applications. It includes a global climate data database of more than 6700 ground stations (monthly solar irradiation and temperature data for the year), energy resource maps (i.e. wind maps), hydrology data, as well as integrated access to NASA climate database. It includes also product data like solar photovoltaic panels' characteristics, wind turbine power curves and clean energy policy and legal toolkits. The software is translated into 30 different languages and is available in two versions [16] RetScreen 4 and RetScreen Plus.

RETScreen 4 is an Excel-based clean energy project analysis software tool that helps decision makers to quickly and inexpensively determine the technical and financial viability of potential renewable energy, energy efficiency and cogeneration projects; this version is written in VBA Excel (Visual Basic for Excel Application).

RETScreen Plus is a Windows-based energy management software tool that allows project owners to easily verify the ongoing energy performance of their facilities; this version is written in C#.

Users conduct a five step analysis, including energy analysis, cost analysis, emission analysis, financial analysis, and sensitivity and risk analysis. RETScreen is used for various types of Renewable-energy and Energy-efficient Technologies (RETs). This program requires at least Microsoft Excel 2000, Microsoft Windows 2000 and Microsoft.NET Framework 2.0 or higher versions and it is also possible to work on Apple Macintosh computers using Virtual Box for Mac, it can also work on Linux based operating system by emulating a windows machine.

Therefore RETScreen can be used for studying wind-diesel systems but it does not consider compressed air storage or WDCAS operation. The main drawbacks for using RETScreen for WDCAS study are:

- The software doesn't have a model for compressed air storage alternative;
- The software doesn't make an hourly balance between production and charge; it makes the assumption that the energy production system is already designed to produce sufficient power to provide the charge at any given time;
- The software doesn't compute the cost of energy;
- RETScreen has no options for importing time series data files [36].

WDCAS:

The WDCAS software developed at the Wind Energy Research Laboratory at Université du Quebec à Rimouski optimizes the WDCAS [37] in terms of number of wind turbines and diesel generators. The software is composed of two main parts, one for the system design and technical calculations [1] , and another doing the financial, environmental and risk analysis. This paper focuses on the second part since the first one has been presented in another paper [37]. The software can do financial calculations, GHG emission reduction evaluations, sensitivity and risk analyses in addition to cost of energy calculations. The software is written in VBA Excel (Visual Basic for Application Excel). This program requires Microsoft Excel 2000, Microsoft Windows 2000 and Microsoft.NET Framework 2.0 or higher and can be launched on Mac or Linux operating systems using a virtual machine.

The program involves the following features:

- General cost analysis
- Wind turbine and diesel generator cost analysis
- Emissions analysis

- Cash flow analysis
- NPV, IRR and COE analysis
- Sensitivity analysis
- Risk analysis

General cost and revenues analysis:

The General Cost Analysis worksheet is used to help the user estimate general costs associated with a project other than the cost of the energy production system. It comprises the feasibility study, the development, the engineering, the electrical components of the production system and the infrastructure. It also includes the annual fees such as the operation and maintenance and the cost of fuel. Finally, it incorporates the annual economies provided by the system which are viewed as revenue from an economic standpoint.

Wind turbine, diesel generator and CAES system cost analysis:

This worksheet provides an input for the production and storage system cost analysis. It includes the cost of the storage system, namely: the reservoir, the flow regulation vane, the compressor, the cooler and the heat exchanger. The user can enter these costs manually or he can use a correlation using the parameters of the equipment such as the pressure, the volume, the flow or the power exchanged. It also includes the cost of the wind turbine and the diesel generator. For all the three components, the software calculates the operation, maintenance and the replacement costs automatically.

Emissions analysis:

The Emission analysis worksheet provides the user with the number tons of CO2 generated by the diesel generator alone, the WDS and the WDCAS systems, respectively. It also provides a comparison between the above-mentioned systems considering the revenues associated with CO2 reduction credit.

Cash flow analysis:

The Cash flow analysis worksheet helps the user to see annual flow of money, in a chart or graphically. It also provides the user the cash flow, the payback and the discounted payback.

NPV, IRR and COE analysis:

In this worksheet, the user observes the annual revenues, before and after actualization. This worksheet provides also the Net Present Value (NPV), the internal rate of return (IRR) and the index of profitability (IP). Finally, this worksheet provides the net present cost (NPC) and the cost of energy (COE).

Sensitivity analysis:

The Sensitivity Analysis worksheet estimates the sensitivity of important financial indicators in relation to key financial parameters, showing the parameters which have the greatest impact on the financial indicators. The sensitivity analysis can be conducted on the NPV, IRR, IP and the payback.

Risk analysis:

The Risk analysis worksheet helps the user to conduct a sensitivity analysis using random changes in key financial parameters. These random changes are conducted by Monte Carlo simulations, and these changes are reported in an impact diagram. This worksheet provides the variation range of the financial indicator, the median and the average value of this indicator. Finally, the user can enter the percentage of risk to evaluate the confidence interval for the financial indicator.

Validation of WDCAS software for a wind-diesel system

In this section, the results of financial, environmental and risk analysis for the same wind diesel system obtained using the WDCAS software are compared with those of HOMER and RetScreen [38].

Technical data:

A mining camp in Canada is used to conduct the comparison between the WDCAS, HOMER and RETScreen software. The camp is owned by a railway company, is located in Newfoundland in a remote area not connected to the grid. The electrical consumption is provided by the camp, and meteorological data from Environment Canada are used for the wind speed. The monthly average electric load of the site is illustrated in Figure 2.

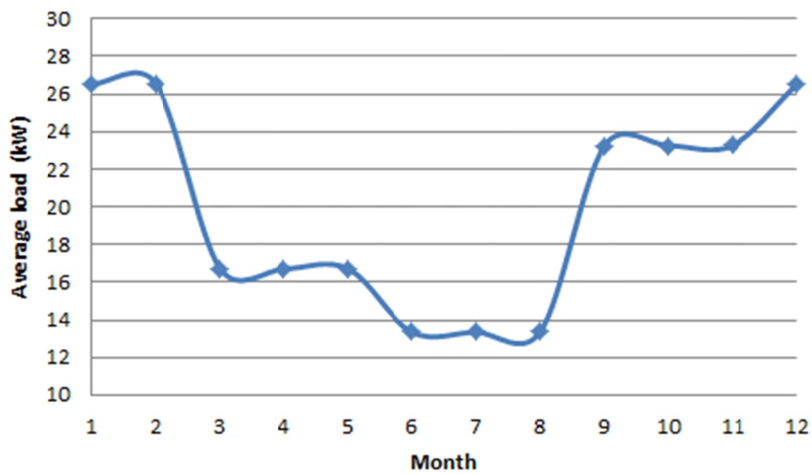

Figure 8: Annual consumption load profile [1]

The average annual load is 19.9 kW, the maximum is 50 kW and the minimum is 7 kW.

Monthly average wind speed data at 10 m, available from Environment Canada in a neighboring site, are illustrated in Figure 3.

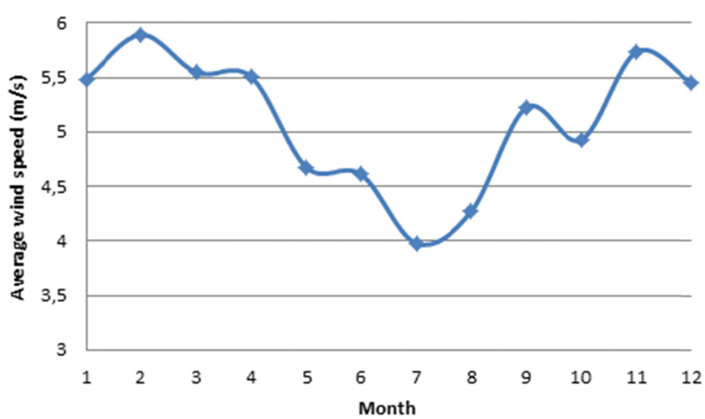

Figure 9: Average wind speed per month [1]

The annual average wind speed is 5.1 m/s. As wind speed probability distribution values are unknown, a Weibull function is considered with a shape parameter of 2 (Rayleigh distribution).

<u>Wind-Diesel system configuration:</u>

The WDCAS software determines the required configuration of the wind-diesel system for a low WPPR (WPPR=40%) according to the load values and wind speed data (Table 2):

Table 2: Wind-Diesel system configuration

	Quantity	Type
Diesel generator	5 x 12 kW	D13-2 Caterpillar
Wind turbine	2 x 10 kW	BWC Excel-S Bergey

The WDCAS software provides the following technical data as well:

- Number of operating hours of diesel engines: 16787 h (3357 hours on average per diesel per year)
- Annual fuel consumption: 56321 L (to be used later for the calculation of annual fuel cost)
- Total Energy produced during a year: 186220 kWh
- The diesel engines' energy counts for 84% of the total energy produced (WEPR=16%)
- The project lifetime is 20 years (used in the financial analysis)

Financial data:

According to available market information [39] [40], the price of equipment, including shipping and commissioning, is estimated as (Table 3):

Table 3: Wind Turbine and Diesel engine cost

	Power	Type	Price
Diesel generator	12 kW	D13-2 Caterpillar	8400 $
Wind turbine	10 kW	BWC Excel-S Bergey	100 000 $

The life span of a diesel engine is 15 000 hours and of the wind turbine is 15 years [41]. The replacement cost of the wind turbine is its initial cost when the lifetime of the equipment expires. For the diesel engines, the lifespan is measured in hours, so the replacement will be the initial cost multiplied by the annual usage ratio i.e. the annual operating hours divided by the lifespan.

The hourly maintenance is estimated to 0,001% of the diesel engine's initial cost [41]. The annual operation and maintenance of wind turbines is estimated as 3% of the initial cost [41].

Therefore, initial cost and O&M costs for the diesel engine are (Table 4):

Table 4: Summary of Diesel Generator related costs

Diesel Generator	Cost

Initial Capital	42 000,00 $
Operations and maintenance	7 104,72 $

For the wind turbine, the initial capital and O&M costs are (Table 5):

Table 5: Summary of wind turbine related costs

Wind turbine	**Cost**
Initial Capital	200 000,00 $
Operations and maintenance	6 000,00 $

In summary, the equipment costs associated with investment and O&M are (Table 6):

Table 6: Summary of equipment related costs

Summary	**Cost**
Initial Capital	242 000,00 $
Operations and maintenance	13 104,72 $

The cost of producing electricity with installation presently on site is estimated to be 1.31 $/kWh and is used as a reference to determine the equivalent annual revenues associated with the wind-diesel system. The fuel price, including transportation costs to the remote area, is estimated to be 2.5 $/L. These prices are particularly high because of the remoteness of the camp. As a result, the annual fuel cost is the fuel price multiplied by the fuel annual fuel consumption (56321 L). Finally, the discount rate is chosen to be 6%. Table 7 presents the annual fuel cost, revenues and discount rate.

Table 7: Annual fuel cost, revenue and discount rate

	Value
Annual fuel cost	140 802,50 $
Annual revenues	244 253,80 $
Discount Rate	6%

<u>Financial analysis:</u>

The financial simulations are performed using HOMER, RETScreen, and WDCAS based on the same data. The comparison is made on relevant financial parameters useful for the study, the results are collected from HOMER, RETScreen, and WDCAS. The available financial results available from WDCAS software are:

- The net present value
- The internal rate of return
- The net present cost
- The cost of energy
- The profitability index
- The payback

It is possible to conduct a sensibility and risk analysis for any one of these financial parameters.

The first comparison is on the results coming from HOMER and WDCAS:

Table 8: NPC and COE comparison in HOMER and WDCAS

Financial indicator	HOMER	WDCAS	Error
NPC	2 445 924,00 $	2 487 816,65 $	1,71%
COE ($/Kwh)	1,10 $	1,1647 $	5,89%

The NPC has a small error compared to the cost of energy. The main reason for COE discrepancy is that HOMER involves a lower energy produced than WDCAS. These differences originate in the technical analysis section of the software and are, most probably, the result of different operating strategies (delays, switch between wind and diesel, minimum operating power for each diesel, compulsory diesel start and minimal operation duration according to specific conditions) between our software WDCAS, and HOMER. The values for annual produced energy calculated using the two software are displayed in Table 9 [1].

Table 9: Total functioning hours of diesel engines of HOMER and WDCAS

	HOMER	WDCAS	Discrepancy
Annual energy (Kwh)	174 687,00	186 220,00	6,60%

In Table 10 the other financial parameters are compared with predictions from Retscreen:

Table 10: NPV, IRR, Profitability index and Payback of HOMER and WDCAS

Financial indicator	RETScreen	WDCAS	Error
NPV	222 299,73 $	219 039,08 $	1,47%
IRR	15,8%	16%	1,98%
Profitability Index	1,9	1,91	0,70%
Payback	6	5,6	5,82%

The error is less than 2% in most cases, due to rounding. For the payback, RETScreen rounds is to an integer which explains the discrepancy in this case. In conclusion, the financial parameters are correctly estimated by the WDCAS software.

Sensitivity Analysis:

The purpose of a sensitivity analysis is to reveal the effect of a certain input change on output values. It helps the decision making process by determining which input optimization will result in maximum output improvement.

In this case study, we compare NPV change due to a variation of up to 10% of the initial investment and the cash flow. RETScreen and WDCAS's results are presented followed by the absolute error for each computation.

The output, in this case the NPV, is displayed in a matrix format considering that total initial investment and cash flow are subject to a change of 10% with an increment of 5%.

We remind the reader with the following average inputs:

- Annual average cash flow for WDCAS : 40 481,78 $ (Average of the annual revenues from selling the energy at 1,31$/kWh minus the expenses i.e. cost of fuel, replacement and O&M for the project lifetime of 20 years)
- Annual average cash flow for RETScreen : 40 527,98 $ (The value contains a rounding error of 0.1%)
- Initial investment : 242 000,00 $

The results of RETScreen:

Table 11: RETScreen sensitivity analysis

	Initial Capital	**217 800,00 $**	**229 900,00 $**	**242 000,00 $**	**254 100,00 $**	**266 200,00 $**
Cashflow	**Variation (%)**	**-10%**	**-5%**	**0%**	**5%**	**10%**
32 422,38 $	**-10%**	177 839,79 $	153 639,79 $	129 439,79 $	105 239,79 $	81 039,79 $
36 475,18 $	**-5%**	224 269,76 $	200 069,76 $	175 869,76 $	151 669,76 $	127 469,76 $
40 527,98 $	**0%**	270 699,73 $	246 499,73 $	222 299,73 $	198 099,73 $	173 899,73 $
44 580,78 $	**5%**	317 129,70 $	292 929,70 $	268 729,70 $	244 529,70 $	220 329,70 $
48 633,58 $	**10%**	363 559,68 $	339 359,68 $	315 159,68 $	290 959,68 $	266 759,68 $

The results of WDCAS:

Table 12: WDCAS sensitivity analysis

	Initial Capital	**217 800,00 $**	**229 900,00 $**	**242 000,00 $**	**254 100,00 $**	**266 200,00 $**
Cashflow	**Variation (%)**	**-10%**	**-5%**	**0%**	**5%**	**10%**
32 385,42 $	**-10%**	177 858,26 $	153 658,26 $	129 458,26 $	105 258,26 $	81 058,26 $

36 433,60 $	**-5%**	224 290,54 $	200 090,54 $	175 890,54 $	151 690,54 $	127 490,54 $
40 481,78 $	**0%**	270 722,83 $	246 522,83 $	222 322,83 $	198 122,83 $	173 922,83 $
44 529,96 $	**5%**	317 155,11 $	292 955,11 $	268 755,11 $	244 555,11 $	220 355,11 $
48 578,14 $	**10%**	363 587,39 $	339 387,39 $	315 187,39 $	290 987,39 $	266 787,39 $

The difference between the NPV computed by RETScreen and WDCAS is calculated as:

Table 13: Difference in sensitivity analysis between WDCAS and RETScreen

	Initial Capital	**217 800,00 $**	**229 900,00 $**	**242 000,00 $**	**254 100,00 $**	**266 200,00 $**
Cashflow	**Variation (%)**	**-10%**	**-5%**	**0%**	**5%**	**10%**
0,114%	**-10%**	**0,010%**	**0,012%**	**0,014%**	**0,018%**	**0,023%**
0,114%	**-5%**	**0,009%**	**0,010%**	**0,012%**	**0,014%**	**0,016%**
0,114%	**0%**	**0,009%**	**0,009%**	**0,010%**	**0,012%**	**0,013%**
0,114%	**5%**	**0,008%**	**0,009%**	**0,009%**	**0,010%**	**0,012%**
0,114%	**10%**	**0,008%**	**0,008%**	**0,009%**	**0,010%**	**0,010%**

The average error in this matrix of differences between RetScreen and WDCAS is about 0.01%, which is very low and is probably due to rounding errors. This means that sensitivity analysis has been correctly implemented in our software WDCAS.

Risk Analysis:

The risk analysis operates as a sensitivity analysis in which the input variation is not fixed but a random value that follows a normal distribution, bounded by a maximum. Each time a random number is generated, the inputs are computed first and then the output; the number of times that a new random number is generated is 500 which is the standard that RETScreen uses. The median of the outputs is displayed as well.

In this section, an impact analysis is added. The purpose is to determine which parameter has most impact on the output; the way it is achieved is different than for the sensitivity analysis as it uses a linear regression from all the outputs computed earlier.

In this case study, the NPV is considered as output. The inputs are the initial investment, the expenses and the revenues. If the expenses are subtracted from the revenues the result is the cash flow (as computed earlier).

The range of change pursued is 10%. This value is the same for all the inputs. First the impact analysis results are summarized in the following chart.

Table 14: Impact of input variables on NPV values in RETScreen and WDCAS

	RETScreen	WDCAS	Error (%)
Initial investment	-0,0671	-0,077852463	16,02%
Profit	0,7395	0,840515259	13,66%
Expanse	-0,6239	-0,748713183	20,01%

The chart shows that a change in the initial investment, revenues and expenses by a random value that follows a normal distribution bounded by 10% change produces the displayed results. As only 500 values are generated, the error is quite high (20%), but still rank the revenues as being the most influential on the NPV.

The median NPV computed from both software is:

Table 15: Error in Median NPV in RETScreen and WDCAS

	RETScreen	WDCAS	Error (%)
Median NPV	219 787,28 $	233 198,00 $	6,10%

The error in the median is low so the risk analysis has been correctly implemented in WDCAS software.

<u>Environmental Analysis:</u>

The environmental analysis is an assessment of the ecological impact of using a particular technology. The metric used to assess the impact will be the CO2 emission of the system used to generate electricity. RETScreen provide the latter feature, therefore it will be used to compare the results from the WDCAS software.

Table 16: Environmental analysis using RETScreen and WDCAS

	RETScreen	WDCAS	Error
Tons of CO2 emission from the wind-diesel energy system	122.07	122.44	0.30%

According to the RETScreen documentation, the diesel emission factor is 0.833 KgCO2/kWh. The same factor is used in the WDCAS to compute the quantity of CO2 emitted by the wind diesel system. 84% of the total energy is generated by the diesel engines according to WDCAS and HOMER software. It is assumed that the wind turbines don’t produce any greenhouse gases. As a result, the total diesel engine’s energy is 84% of 186 MWh, approximately 156 MWh. The CO2 emissions have an error of 0.3% due to rounding.

Although WDCAS software is validated only for wind-diesel systems available in RetScreen and HOMER, we expect a similar accuracy level when compressed air storage is used. The financial analysis of using compressed air storage with the wind-diesel system is presented in the next section.

WDCAS performance:

In this section, the WDCAS software is used to assess the performance of a wind-diesel system with compressed air storage. The data from the previous case study are used to determine WDCAS performance improvement due to compressed air storage. The analysis is based on ideal operating conditions as explained in the next section and has been performed for the same low wind power penetration as for the wind-diesel system. It has to be mentioned that a high wind power penetration level is required to optimize the financial impact of using energy storage [10]. This case study is used only to illustrate the software functionality and an optimization procedure is required to improve financial parameters of the wind-diesel system with CAES.

Technical data:

Ideal operating conditions include an infinite storage in the sense that there are no volumetric and energetic constraints related to the storage of compressed air and its use, among other conditions. The operation scenario is based on the following assumptions:

- The volume of the tank is “infinite”. Tank size is such that the system can store excess energy at all times, with no volumetric and energetic constraints. Storage system parameters, i.e. storage pressure and autonomy are chosen accordingly.
- The minimum allowable power for storage is zero. That means that any excess power is used for storage or, in other words, the power dissipated by the system is zero.
- The number of compressor stages must be the highest possible to improve the compression performance.
- The compression is done under the following conditions: pressure of the outdoor air (1 bar), storage temperature (20 ° C) and the polytropic exponent of air (n = 1.3).

Based on these assumptions, the ideal scenario used for this study is presented in this Table.

Table 17: Assumption for storage system [1]

Data	Value
Number of compressor stages	7
Polytropic exponent	1.3
Atmospheric pressure	1 bar
Storage temperature	20°C
Polytropic efficiency	100%

Compressor motor efficiency	100%
Minimum allowable power for storage	0 kW
Storage pressure	2 bars
Number of days of autonomy	1000 (infinite tank volume)

The compressor and the tank chosen are the following:

Table 18: Tank and compressor size

Storage System	Quantity
Tank	5400 L
Compressor	37 Kw

The results of the simulation in each configuration, Diesel only, WD (Wind-Diesel) and WDCAS (Wind-Diesel with Compressed Air Storage) are summarized as:

Table 19: Results of WDCAS software

Results	
Minimal load	7,00 kw
Average load	19,92 kw
Maximal load	50,00 kw
Average wind speed	5,10 m/s
Only diesel consumption	66614 L
WDS diesel consumption	56321 L
WDCAS diesel consumption	49525 L

Generator operating hours at 30% of his nominal power	
WDCAS	
supercharged	143 h
no supercharged	2079 h
WDS	
no supercharged	3035 h
Diesel only	
no supercharged	3555 h

Dissipated power	
Diesel only	5728 kW
WDS	5877 kW
WDCAS	0 kW

Results analysis indicates that WDCAS, with a low WPPR (40%), requires 49525 L of fuel, a saving of 12% compared to the wind-diesel system (56321 L) and 25,6% compared to diesel only mode (66,614 L).

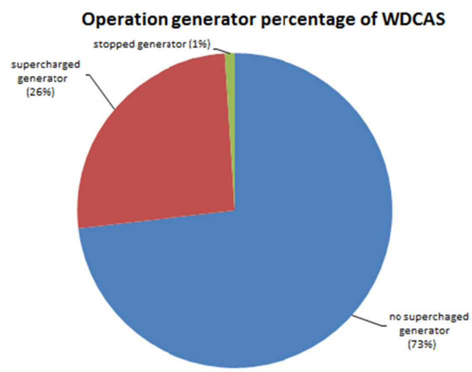

Figure 10: Functioning distribution of diesel engine in the WDCAS

The results show that the operation of the system involves the use of generators in supercharged mode for 26% of the time against 73% in normal use (1% they are completely stopped) for this low penetration scenario. Fuel savings of approximately 27% with a low WPPR and when compared to diesel only operation.

The number of operating hours of diesel engines in WDCAS mode is 16916 h, higher than for WD mode as diesel engines are used more often at 30% of their nominal power in supercharged mode. Accordingly, the O&M cost is going to be higher in the financial data.

Finally, no power is dissipated for the operation under ideal conditions; any surplus power is used to store compressed air when available.

Financial data:

To conduct the financial analysis for the WDCAS power plant, the financial data is necessary. The cost of diesel engines and wind turbines is presented in the previous financial analysis. The costs for the air storage system are:

Table 20: Tank, compressor and labor cost

Storage System	Unitary Cost	Total Cost
Tank	50 $/L	270 000.00 $
Compressor	459.45 $/Kw	17 000.00 $
Labor	35000$	35000$

These values are the same chosen to size the WDCAS power plant in the Wind Energy TechnoCentre in Gaspé, Québec. It is assumed that the labor to assemble the system is approximately 35000 $. Operation and maintenance annual costs for the storage systems are evaluated to be 1% of the investment cost.

Table 21: O&M and total initial cost of the tank and the compressor

	Cost
O & M	2 870.00 $
Total Initial Capital	287 000.00 $

Other changes occur in the costs of the diesel engine, since the number of functioning hours is changed, therefore the replacement and the O&M become:

Table 22: Diesel generator related costs for WDCAS

Diesel Generator	Cost
Initial Capital	42 000.00 $
Operations and maintenance	7 104.72 $

As a summary, the total cost for equipment cost is:

Table 23: Equipment related costs for WDCAS

Summary	Cost
Initial Capital	564 000.00 $
Operations and maintenance	15 920.54 $

In this case study, the other technical data remain the same:

- The cost of energy serving to determine the annual revenues is estimated to 1,31 $/KWh
- The fuel price is estimated at 2,5 $/L
- Discount rate of 6%

As a result, the annual fuel cost and revenues are:

Table 24: Annual fuel cost and revenues for WDCAS

	Cost
Annual fuel cost	206 642,02 $
Annual revenues	244 246,15 $

Financial analysis:

In this section all the financial data and the technical data will be used as inputs in the WDCAS software. The outputs need for the financial analysis are listed below:

- The net present value

- The internal rate of return
- The profitability index
- The discounted payback
- The net present cost
- The cost of energy

All these values allow the plant designer to assess the profitability of the WDCAS system. The following chart is a summary of these values generated by the WDCAS software.

Table 25: Financial parameters for the WDCAS

Financial Parameter	Value
Net Present Value	-100 967,34 $
Internal Rate of Return	3,5211%
Profitability Index	0,81
Discounted Payback	28,26938481
NPC	2 806 840,44 $
Cost Of Energy	1,3141 $

Since the initial capital is high, the net present value is very low, this is due to the fact that the profits are not high enough to support all the expenses and to grant a substantial income. Again, the profit allow a low internal rate of return.

The profit index (PI) on the other hand is less than one, the bigger the PI the better. In this case it is the result translates to a low profitably in the project and a high initial investment. Next, the payback is higher than the project life time. Again this is caused by the composition of the annual fees, the initial capital and the profit. The NPC and the cost of energy are properly issued and reflect the high costs of the system.

The following table resumes the differences between WDCAS and WD system:

Table 26: Difference of financial parameters in WDCAS and WD

Financial Parameter	WDCAS Value	WD Value	Difference between WDCAS and WD
Net Present Value	-100 967,34 $	219 039,08 $	316,9%
Internal Rate of Return	3,52%	16%	-354,4%
Profitability Index	0,81	1,91	-135,8%
Discounted Payback	28,26938481	8,036704624	71,6%
NPC	2 806 840,44 $	2 487 816,65 $	11,4%
Cost Of Energy	1,31 $	1,16 $	11,4%

The NPV of WDCAS project is lower than in the WD system, due to higher initial investment. The IRR is lower for WDCAS as the initial investment is higher. The PI is lower and payback longer for WDCAS compared to WD. The NPC and COE are both higher for WDCAS compared to WD because of the high initial investment.

Sensitivity analysis:

The sensitivity analysis is applied to the NPV with a variation of 10% of the annual cash flow and Initial capital. The cash flow is the difference between annual revenues and the replacement, operations and maintenance and fuel costs.

The following data is necessary to conduct a sensitivity analysis:

- Average annual cash flow : 37 604,13 $
- Initial investment : 564 000,00 $

The results of the sensitivity analysis of WDCAS system are as follows:

Table 27: WDCAS sensitivity analysis

	Initial Capital	**507 600.00 $**	**535 800.00 $**	**564 000.00 $**	**592 200.00 $**	**620 400.00 $**
Cashflow	**Variation (%)**	**-10%**	**-5%**	**0%**	**5%**	**10%**
30 083,30 $	**-10%**	-78 146,87 $	-131 046,87 $	-183 946,87 $	-236 846,87 $	-289 746,87 $
33 843,72 $	**-5%**	-35 015,23 $	-87 915,23 $	-140 815,23 $	-193 715,23 $	-246 615,23 $
37 604,13 $	**0%**	8 116,41 $	-44 783,59 $	-97 683,59 $	-150 583,59 $	-203 483,59 $
41 364,54 $	**5%**	51 248,05 $	-1 651,95 $	-54 551,95 $	-107 451,95 $	-160 351,95 $
45 124,96 $	**10%**	94 379,69 $	41 479,69 $	-11 420,31 $	-64 320,31 $	-117 220,31 $

A variation in the inputs as low as 10% can produce dramatic changes in the average NPV. For instance, a raise of 10% in the initial investment and a reduction of 10% the cash flow result in a 100% reduction of the average NPV, to a level similar to the one of the WD system. On the opposite hand, a reduction of 10% in the initial investment and a raise of 10% in the cash flow result in a 100% increase of the NPV.

Risk analysis:

In the risk analysis, Monte Carlo simulations are applied to determine the most impactful parameter on NPV. A random variation by a maximum of 10 % for all the financial parameters affecting NPV i.e. initial investment, maintenance and replacement cost, fuel cost and the yearly revenues. This variation follows a normal distribution centred in 0 with a standard deviation of 1/3. The variation is the same for all the financial parameters.

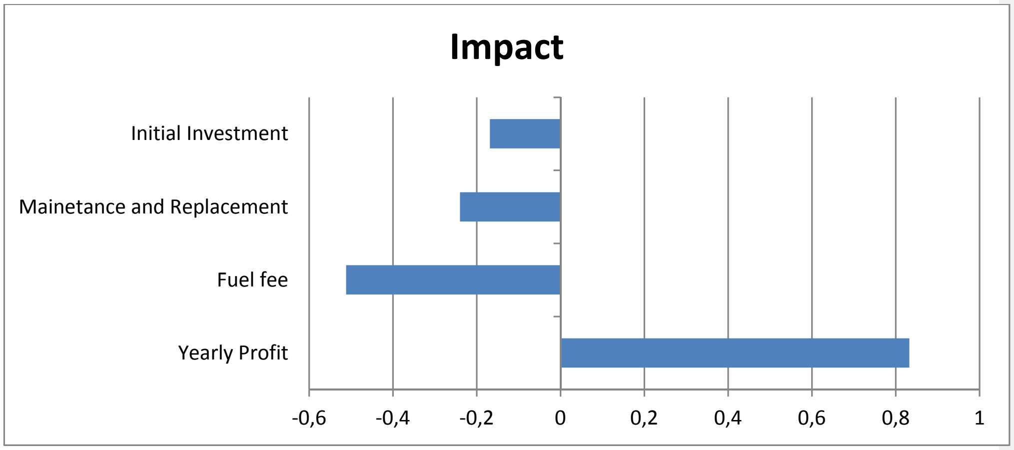

Figure 11: WDCAS Impact Diagram

The impact analysis reveals that the annual revenue has the largest influence on NPV. Its impact is "positive" which means that an increase in the annual revenues induces a raise in the NPV. The fuel cost has a "negative" impact, in other words an increase in the fuel cost results in a drop of NPV.

The probability distribution of the NPV obtained with the Monte-Carlo simulation is illustrated in the graph of Figure 6. The NPV follows a normal distribution.

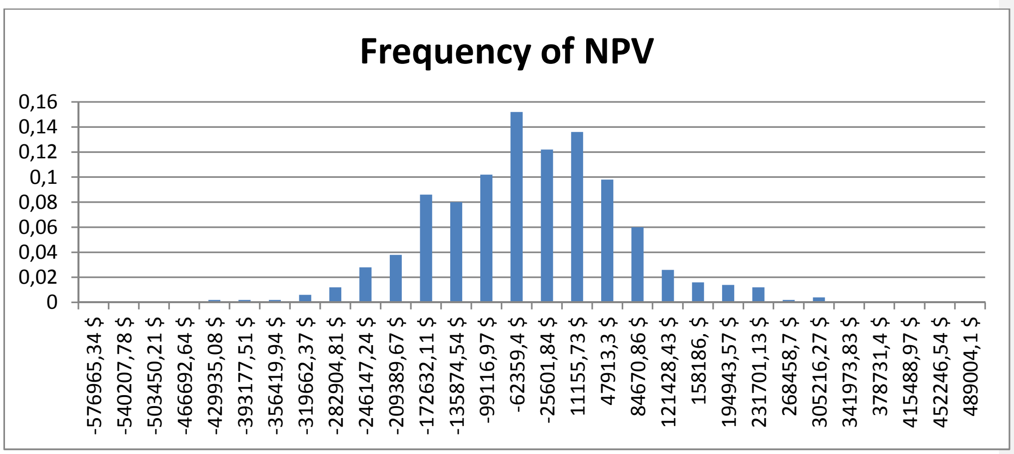

Figure 12: NPV probability distribution for WDCAS

For a risk rate of 15%, the confidence interval and the median are easily found using the WDCAS software, the following table summarizes the results:

Table 28: WDCAS risk analysis

Risk Rate	15%
Median	-102 284,82 $
Upper limit of the confidence interval	-255 422,34 $
Lower limit of the confidence interval	45 479,55 $

The median is a center value of all the values generated by the simulations, it is very close to the one projected in sensitivity analysis. The confidence interval is reasonable according to the inputs. The upper limit is close to the forecasted value in the previous analysis, however the lower limit is different probably due to combined impact of all factors and the way random numbers are generated.

Environmental analysis:

To determine the environmental impact of using a WDCAS instead of a WD system, the CO2 emissions are compared in the following table:

Table 29: WDCAS environmental analysis

	WDCAS	WD	Difference
Tons of CO2 emission	106.75	122.44	-14.69%

The use of the WDCAS system reduces by almost 15% CO2 emissions. It is mainly due to the use of compressed air which results in lesser fuel consumption for the same power output. This translates into a better efficiency and less CO2 emissions.

1.1 CONCLUSION:

In this paper, a new the financial and environmental analysis software named WDCAS, for hybrid wind-diesel systems with compressed air storage, has been developed. WDCAS features encompass the ones of existing software with similar functionality as RETScreen and HOMER. When applied to similar wind-diesel systems, WDCAS provides similar results for all financial and environmental parameters as commercially available software. Finally, the WDCAS has been applied to study environmental and financial impact of adding compressed air storage to an existing wind-diesel system. Even with a low, non-optimal wind power penetration rate the addition of compressed air storage improved some of the financial indicators of the project. Even with an initial cost of WDCAS significantly higher than for a WD system, additional revenues, including the ones associated with a Carbone tax, may result in a system with better economics. We are presently using this tool for optimizing the configuration of a WDCAS system to improve the financial and environmental feasibility of a mining camp project in Northern Quebec. The results will be published in a future paper.

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Commentaire [AI1]: Utiliser la traduction littérale du titre de l'article lorsque finalisé.

CHAPITRE 3
ANALYSE FINANCIERE, ANALYSE DE SENSIBILITE, DE RISQUE ET ETUDE D'IMPACT ENVIRONNEMENTALE DU SHEDAC POUR LE CAMP ESKER

3.1 RESUME

Dans cet article, est présenté une analyse financière d'un SHEDAC optimal destiné pour l'électrification du camp minier d'Esker, un site isolé situé dans le Nord-du-Québec. Une étude réalisée à permit de répondre à la problématique énergétique du camp issue d'un usage peu efficace de la génératrice diesel présentement en place. Afin de réaliser cette tâche, le logiciel de dimensionnement élaboré et présenté dans le premier article est utilisé, puisqu'il est parfaitement conçu pour ce type d'analyse [28] [76]. Des solutions ont été proposées pour la réduction de la consommation énergétique de plusieurs façons :

1- Une réduction de la consommation énergétique globale du site a été réalisée. En effet, certains postes (chauffage, éclairage) présentent des consommations et des usages totalement inappropriés par rapport à la vie sur le site. Leurs réductions a permis de diminuer la consommation énergétique annuelle moyenne du camp d'environ 30 % ;

2- Une analyse technique a été réalisée déterminer le SHEDAC optimal pour l'implantation sur le site du camp Esker.

Le système optimal, qui a finalement été retenu, permet des économies d'environ 70% par rapport à un système composé uniquement de génératrices. Outre les économies énergétiques, la solution proposée présente de grands avantages financiers et écologiques. Une réduction d'environ 54% de GES et une réduction de 25% environ du coût de l'énergie prouve ce point. Ces résultats ont été obtenus pour un taux de pénétration en puissance éolienne fixé à 65%. Une comparaison a été menée afin de tenter d'optimiser la consommation de carburant en augmentant le taux de pénétration en énergie éolienne

(100%). Ce changement, même si augmente le coût de l'installation, résulte en une augmentation de la valeur actuelle nette du projet d'environ 12%.

Finalement, les résultats proposés dans cet article permettent de mettre en évidence les bénéfices de l'implantation d'un SHEDAC pour un site isolé et le potentiel des logiciels développés pour l'analyse financière, de risque et environnementale.

ENVIRONMENTAL, FINANCIAL AND RISK ANALYSIS FOR A HYBRID WIND-DIESEL SYSTEM WITH CAES FOR A REMOTE MINING CAMP IN CANADA

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Nomenclature:

- WPPR : Wind Power Penetration Rate
- WEPR : Wind Energy Penetration Rate
- WDCAS : Wind–Diesel-Compressed Air Storage
- CAES : Compressed Air Energy Storage
- GHG : Green House Gas
- WDS: Wind Diesel hybrid System
- GUI: Graphical User Interface
- IRR: Internal Rate of Return
- NPV: Net Present Value
- NPC: Net Present Cost
- IP: Index of Profitability
- COE: Cost of Energy
- λ : Stoichiometric air/fuel ratio
- η_e : Electric efficiency of the wind turbine
- η_{i_DE} : Indicated efficiency of the engine
- η_{p_C} : Polytropic efficiency of the compressor
- η_{tr} : Transmission efficiency between the engine and the compressor
- η_{v_DE} : Volumetric efficiency of the engine
- π_C : Total compression ratio

- π_{i_C} : Compression ratio for each stage
- ρ_a : Air density
- A : Fuel consumption parameter
- B : Fuel consumption parameter
- c : Scale parameter (Weibull distribution)
- C_{P_WT} : Power coefficient
- E_{an_CH} : Annual energy consumption of the charge
- $E_{\bar{v}_w}$: Annual energy production of the wind turbine
- $f(v_w)$: Weibull density probability function
- h_{WT} : Wind turbine hub height
- h_0 : Reference height
- k : Shape parameter (Weibull distribution)
- $\dot{m}_c$: Compressed air mass flow (from the compressor)
- $\dot{m}_{f\_DE}$: Fuel mass flow injected in cylinders
- $\dot{m}_{in\_DE}$: Air mass flow entering the engine
- $\dot{m}_u$: Capacity of a storage unit
- n_c : Polytropic index
- N_c : Number of compressor stages
- N_{max_unit} : Number of maximum storage units
- NB_{WT} : Number of wind turbines
- ND_{auto} : Number of days of autonomy
- p_a : Inlet atmospheric pressure of the compressor
- p_{ou_C} : Outlet pressure of the compressor
- p_{in_DE} : Inlet pressure of the diesel engine
- p_{st} : Storage pressure
- P_C : Power of the multi-stage compressor
- P_{C_1} : Power of the single-stage compressor
- P_{CH} : Power of the charge
- P_{CH_ave} : Average power of the charge
- P_{DE} : Power of the diesel engine
- P_{EM} : Minimal power required to start the electric motor of the compressor
- P_{EX_WT} : Excess wind power
- P_{max_CH} : Maximum power of the charge
- P_{max_WT} : Maximum wind turbine power
- P_{nDE} : Nominal diesel engine power
- $P_{WT}(v_w)$: Wind turbine power
- $P_{WT\_a}(v_w)$: Wind power
- PCI : Indicated lower calorific value of the fuel
- R : Perfect gas constant for the air
- S_{WT} : Swept area
- t_{step} : Time step
- t_{total} : Duration of the simulation
- T_{st} : Storage temperature

- V_{st} : Total volume of the storage
- v_w : Wind speed
- v_{0_w}: Wind speed at the reference height
- α : Wind shear coefficient

Abstract:

Most of the remote areas around the world use diesel generators to produce electricity. The cost and environmental impact of the diesel requires an increased use of renewable energy sources. As such, the Wind-Diesel hybrid System with Compressed Air energy Storage (WDCAS) is one of the best alternatives in remote areas. Although the research in this area is new, it has already proved to be a suitable solution for electricity production. The technical analysis has been presented in a previous study, in this paper, the financial analysis is done to assess the feasibility of the system. This technology proves to be cost effective and has a high Net Present Value (NPV) and Internal Rate of Return (IRR), with low risk and a low cost of energy (COE). On the other side, the environmental impact is positive as less fuel is used. The WDCAS system is an advantageous strategy for increasing renewable energy penetration rates and a suitable power generator for remote areas.

Introduction:

Canada has one of the widest territories in the world, it has a dense population in the south but very scarce in the north, with numerous remote areas and isolated villages not connected to the main electricity grids [41] [53] [40] [46] [5]. As a result, the diesel engines are the main source of electricity due to their stability and reliability. The main drawback of this electrical production system is its inefficiency in three areas: the cost, the environment and the system itself [62] [85] [57] [9]. First, the cost of kilowatt hours using diesel engines is high and further increased by the transportation fees thus making it very expensive [36] [43]. The second drawback is the environmental one; the diesel fuel is responsible for greenhouse gas emissions. Finally, the diesel engine should operate at more than 30% of its nominal capacity to maintain an acceptable efficiency which means at certain moments will produce more than what is required for the charge [12] [61]. One solution to solve these problems is the use of renewable energy, environment friendly and cost efficient when sufficient resource is available locally.

North of Quebec has abundant wind resources and is a suitable location for hybrid wind-diesel systems with storage, most of the time using batteries. This ensures a lower operation time of the diesel engine below 30% of its capacity by compensating with wind or stored energy. The use of wind turbines reduces significantly the greenhouse gas (GHG) emissions and lowers the expenses associated with fuel and maintenance [53] [40] [62] [38] [86].

The use of compressed air as a storage technology can further improve the system performance as it will ensure the optimal operation of diesel engines at all regimes. Such a system is called wind diesel with compressed air storage (WDCAS) [52] [86] [51]. During strong wind periods, the turbines can provide enough electrical energy for the load and the surplus serves to compress and store air. During low wind periods, compressed air is used to overcharge the diesel engine such as it operates at all regimes with an optimal air/fuel ratio. The pneumatic hybridization of the diesel engine improves its efficiency, the torque and the power and results in the reduction of the fuel consumption, cost and GHG emissions. The hybrid WDCAS system requires additional equipment for compressed air management as shown in the following figure [41] [53] [46] [62] [38] [86] [56] [42] [87] [59] [22] [23]:

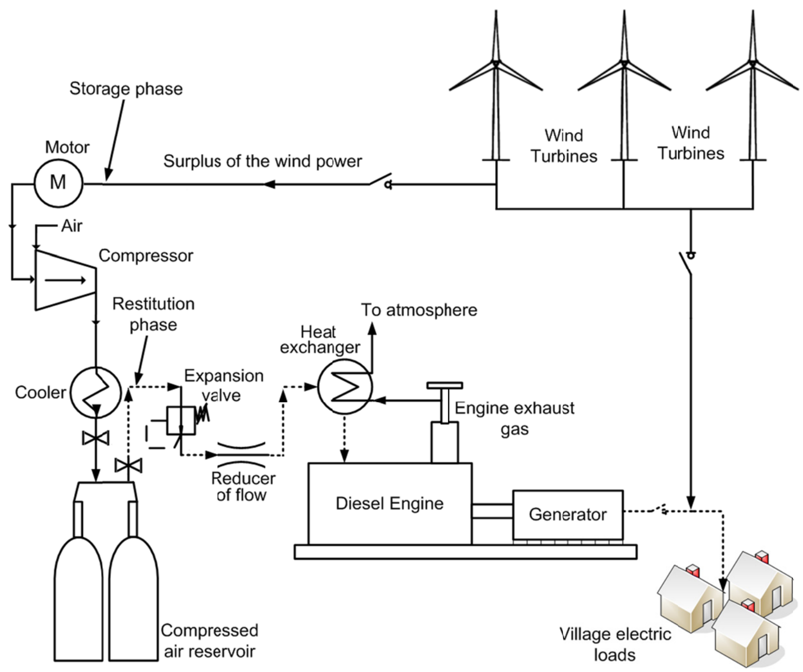

Figure 13: WDCAS Technology [24]

In general, to improve the overall efficiency, the WDCAS uses a high wind power penetration rate (WPPR), defined as the ratio between the installed wind power and the maximum value of the charge. WPPR is commonly higher than 100% for wind-diesel systems with compressed air storage which allows diesel stopping during periods of strong winds. Therefore, the operation of the WDCAS depends of the available wind speed as follows:

- Strong winds: the wind energy supplies all the load of the remote site; the surplus, if available, is used to drive a compressor and to store the compressed air in an air tank.

- Weak winds: the wind energy provides partially the load, the balance is ensured by the diesel engines, overcharged with the stored compressed air such that an optimal air/fuel ratio is available at all operation regimes.

Financial analysis helps determine the feasibility of a project. They include cost, profit and risk forecasting. On the other hand, the environmental issues have given birth to new markets, making an eco-friendly product a business leverage compared to competitors. In this paper, the financial and environmental parameters of a WDCAS system, designed to provide energy to a mining camp in Northern Quebec, are studied to determine the project feasibility. Recently, a technical design tool for WDCAS systems has been developed to determine the best configuration of the different components according to specific objectives as the lowest cost of energy (COE) or the lowest fuel consumption [25] [24]. A financial, sensitivity, risk and environmental analysis software has been also presented as a decision tool to determine the feasibility of WDCAS systems [26].

These tools are applied in this research to determine the financial feasibility and environmental benefits of the implementation of a WDCAS system in a real site, the Esker mining camp in Northern Quebec.

Model of the Wind-Diesel System with Compressed Air Storage (WDCAS):

The physical models and the characteristics of the software used for each subsystem are presented in this section.

Basic parameters

Simulation time and time step:

The user can choose the duration of the analysis (t_{total}) and the time step (t_{step}) for the simulation. This time step time is the same for the load and meteorological data. The default value is $t_{step}=1h$.

Energy balance:

The software uses the following energy balance equation at every time step over the complete duration of the simulation:

$$Load \ = Wind\ Turbine\ Power + Diesel\ Generator\ Power - Power\ Compressed\ Air\ Storage \qquad (1)$$

For each time step, diesel generator power and/or the power used for compressed air storage are adjusted to estimated load and available wind power. Function of the load, the wind resource and the storage level, the power terms are calculated.

Subsystems modeling

Load

The software does not use any specific model for the load; the user should provide this data for each time step according to each specific project.

Wind Turbine Power:

The wind turbine instantaneous power (energy if we consider it over one time step) is determined by the average wind speed at that particular moment (or time step) and the type of wind turbine.

The wind turbine (WT) power curve represents the variation of the power output with the wind speed $P_{WT}(v_w)$ and is provided by each manufacturer. Energy production over a given time period will consider both wind turbine power curve and wind speed distribution. As an example, the annual energy production is:

$$E_{\bar{v}_w} = 8760 \sum_{v_w=0}^{v_w=25} P_{WT}(v_w) f(v_w) \quad (2)$$

with Weibull distribution defined as:

$$f(v_w) = \left(\frac{k}{c}\right)\left(\frac{v_w}{c}\right)^{k-1} \exp\left[-\left(\frac{v_w}{c}\right)^k\right] \quad (3)$$

Weibull distribution represents the probability to have a certain wind speed. Its parameters, c (scale factor) and k (shape factor) are characteristics of the site and should be provided by the user. If only average wind speed is known at the site, then k is assumed equal to 2 (k=2, Rayleigh distribution) and c is computed.

One of the main characteristics of a hybrid system is the wind power penetration rate defined as the ratio of installed wind power capacity to maximum load:

$$WPPR = \frac{P_{\max\_WT}}{P_{\max\_Load}} \quad (4)$$

Similarly, the wind energy penetration rate represents the share of wind energy in total energy over a given period of time, generally one year:

$$WEPR = \frac{E_{\bar{v}_w}}{E_{Load}} \quad (5)$$

These characteristics are important as different system topologies, operation strategies and economic parameters are specific to each low, medium or high penetration level of wind energy. In the software, the user should define the desired WPPR level of the system. According to this value, the software determines the number of wind turbines needed:

$$NB_{WT} = \frac{P_{\max\_Load} * WPPR}{P_{WT}(v_w)} \quad (6)$$

Using all this data, the software will generate wind speed over the entire period of analysis and determine wind power at each time step.

Diesel Generator Power:

The WDCAS simulation software allows one or more diesel generators operating in a "normal mode" (without compressed air for overcharging) and/or supercharged with compressed air. For a normal operation, fuel consumption is determined based on the diesel required power and its technical characteristics using:

$$\dot{m}_{f\_DE} = A \cdot P_{DE} - B \quad (7)$$

where A and B are technical parameters of the diesel generator used. The indicated efficiency is determined as:

$$\eta_{i\_DE} = \frac{P_{DE}}{PCI * \dot{m}_{f\_DE}} \quad (8)$$

In supercharged mode, the stored compressed air is used such as to maintain an air/fuel ratio (□) value resulting in optimal diesel efficiency. Air/fuel (□) ratio is defined as:

$$\lambda = \frac{\dot{m}_{in\_DE}}{\dot{m}_{f\_DE}} \quad (9)$$

Previous studies have shown that maximum efficiency of the diesel engine ($\eta_{i_{DE}} \cong 56\%$) is reached for an air/fuel ratio of □≅53 [61]. Therefore, the software will consider this optimal ratio for all overcharged operation regimes. The fuel rate and compressed air flow rate required to supercharge the diesel are determined by the following equation, where we consider $\eta_{i_{DE}}$=56% :

$$P_{DE} = PCI * \eta_{i\_DE} * \dot{m}_{f\_DE} = PCI * \eta_{i\_DE} * \frac{\dot{m}_{in\_DE}}{\lambda} \quad (10)$$

Compressed air storage

The compressor type determines how is used the excess of wind energy over the charge resulting from equation (1) and the size of the storage tank. Subsystem modeling uses physical parameters related to air compression phenomena. The software hasn't pre-defined compressors and the user should configure them according to the specific situation.

The relation between power and compression ratio of a single-stage polytropic compressor [61] is defined by:

$$P_{C\_1} = \frac{n_C}{n_C - 1} * \dot{m}_C * R * T_{st} * \left[\left(\frac{p_{ou\_C}}{p_a} \right)^{\frac{n_C - 1}{n_C}} - 1 \right] * \frac{1}{\eta_{p\_C}} \quad (11)$$

The most convenient solution to increase the compression ratio is to combine several single-stage compressors or directly use a multi-stage compressor. We are considering identical compression ratio for each stage of the compressor, as follows:

$$\pi_{i\_C} = \frac{p_1}{p_a} = \frac{p_2}{p_1} = \frac{p_2}{p_3} = \cdots = \frac{p_{N_C} (=p_{ou\_C})}{p_{N_C - 1}} \quad (12)$$

The resulting compression ratio for the whole compressor, defined as the ratio between the outlet and atmospheric pressure will be:

$$\pi_C = \frac{p_{ou\_c}}{p_a} = \left(\pi_{i\_C}\right)^{N_c} \qquad (13)$$

We are considering that the outlet pressure is identical to the storage pressure and its value is provided as an input data by the user. The relation between the multi-stage compressor power and compressed air mass flow rate becomes:

$$P_C = \frac{n_C N_C}{n_C - 1} * \dot{m}_C * R * T_{st} * \left[\left(\frac{p_{ou\_C}}{p_a}\right)^{\frac{n_C - 1}{n_C N_C}} - 1\right] * \frac{1}{\eta_{p\_C}} \qquad (14)$$

In the meantime, this compressor power is equal to wind power surplus adjusted with electric motor and transmission efficiency:

$$P_C = P_{EX\_WT} \cdot \eta_{tr} \cdot \eta_e = (P_{WT} - P_{CH}) \cdot \eta_{tr} \cdot \eta_e \qquad (15)$$

Storage tank

The key parameter of this subsystem is the storage unit which represents the quantity of compressed air coming out from the tank that is required to supercharge the diesel such as to deliver a power equivalent to the average charge, during one time step (generally one hour). The assumption of an optimal supercharging of the diesel is made. Thus, the maximum efficiency of the diesel engine ($\eta_{i_{DE}} \cong 56\%$), reached for an air/fuel ratio of □≅53 are used to determine the storage unit as follows:

$$\dot{m}_u = \frac{\lambda * P_{CH\_ave}}{\eta_{i\_DE} * PCI} \qquad (16)$$

The user should provide the number of days of autonomy ND_{auto} during which the system should provide energy without wind, by using only the supercharged diesel generator. As a result, the required number of storage units is:

$$N_{\max\_unit} = ND_{auto} * 24 * 3600 * \frac{t_{step}}{1\ Hour} \qquad (17)$$

If the time step is one hour (which is usually the case) the last term in the equation is equal to unity. The volume of the storage tank will be:

$$V_{st} = \frac{N_{max\_unit} * \dot{m}_u * R * T_{st}}{p_{st}} \qquad (18)$$

According to each operating scenario, the software determines the required number of diesel generators to operate. If the system operates only with generators, this number is calculated as follow:

$$NB_{DE} = \left|\frac{P_{Load}}{P_{nDE}}\right| + 1 \qquad (19)$$

If the system operates with generators and wind turbines, this number is calculated as:

$$NB_{DE} = \left|\frac{P_{Load} - P_{WT}}{P_{nDE}}\right| + 1 \qquad (20)$$

Case study

Location of Esker Camp

The Esker camp is located 72.3Km south of Schefferville and the only terrestrial access is by rail. The company providing this rail transportation service, Tshiuetin, which means "North Wind" in aboriginal, operates 132.5 miles of railway connecting Emeril (Labrador) and Schefferville.

The train that leaves Sept-Îles toward Schefferville is used to supply the city with fuel, food and goods in general. The train stops in Esker, a camp used for mining services; it is open only from May to November of each year. The following illustrations are the camp in real life.

Figure 14: Esker site view 1

Figure 15: Esker site view 2

Energy consumption

As the camp is located in a remote area, not connected to the grid, it should produce its own electricity. Currently, a 150 kW diesel engine is used supply the site with its electrical needs. It is this same source that is used to heat the building and water, for lighting, water pumping, refrigerators and general appliances. The consumption profile is illustrated in Figure 4 for September 28th, 2014 between 9h00 and 22h00, the time step used is 12 seconds. As in the WDCAS software the time step is 1 hour, an hourly average of the 300 values with a time step of 12 seconds is computed.

Commentaire [AI2]: Quel est le pas de temps utilisé dans cette figure? Selon ce qui est dans le document, nous parlons d'un pas de temps d'une heure en général.

Commentaire [Y3]: OK

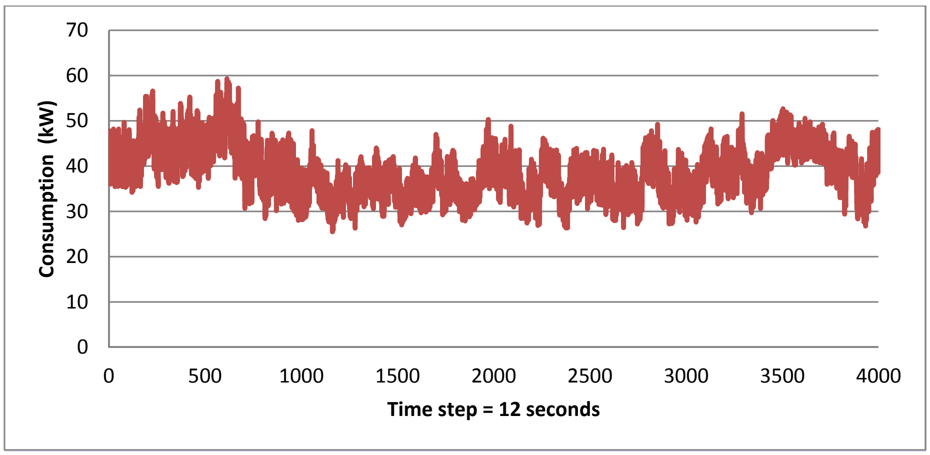

Figure 16: Consumption profile on the site for 28 September 2014 between 9a.m and 10p.m with a time step of 12 seconds

Commentaire [AI4]: À réviser. Quel est le pas de temps utilisé? Est-ce que ce sont des données à chaque minute? Dans le logiciel nous utilisons un pas de temps d'une heure en général donc quel est le lien avec ce graphique? Il faut avoir une ligne dans le graphique qui soit mieux définie, il ne sera pas possible de publier cette image dans un article scientifique.

Commentaire [Y5]: OK

<u>Analysis of the current situation:</u>

As illustrated in Figure 4, the average consumption is 40 kW, with a minimum of 25 kW and a maximum of 60 kW.

From a first estimate, we have these conclusions:

- The 150 kW diesel generator is largely oversized for the camp. The annual fuel consumption of the current system is about 112420 L, which represents an annual cost of 281 050 $ for a fuel cost of 2,5$/L.
- There is only one power source available, which means that when the engine fails to work properly there is not enough backup; the 6.5 kW emergency generator is too small to satisfy all the electrical demand.
- Obviously, the energy equipment is not optimized for the charge of the camp, it is oversized for the electrical needs and should operate most of the time at low efficiency regimes.

The following modifications have been identified to improve the energy system of the camp:

- Reduce the consumption by using energy efficient appliances.
- Replace the diesel with a WDCAS system with wind turbines and compressed air storage.

After implementation of energy efficiency measures, namely by using energy efficient appliances and changing the lighting system, the new consumption profile is illustrated in Figure 5 for the seven months of operations from May (#1) to November (#7).

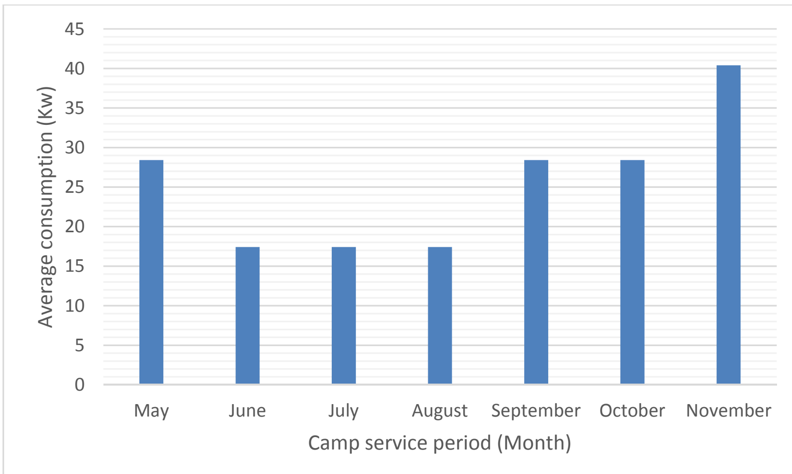

Figure 17: New profile established for the average annual consumption of Esker Camp

Commentaire [AI6]: Tu dois indiquer quel mois correspond à quel numéro sur l'abscisse. Même si tu as mentionné dans un paragraphe précédent que le camp opère seulement 7 mois par année, il n'est pas clair quel numéro correspond à quel mois.

Commentaire [Y7]: OK

Proposed Solutions using WDCAS:

Wind-Diesel system configuration

The WDCAS software determines the required configuration of the wind-diesel system for a low WPPR (WPPR=65%) and a high WPPR (100%) according to the load values and wind speed data, as follows:

Commentaire [AI8]: Combine the 2 WPPR values in the same tables. The results should appear in parallel.

Commentaire [Y9]: OK

Table 30: Wind-Diesel system configuration for WPPR=65% (left) and WPPR=100% (right)

	Quantity (WPPR=65%)	Quantity (WPPR=100%)	Type (WPPR=65% and 100%)
Diesel generator	2 x 27kW	2 x 27kW	D30-8 Caterpillar
Wind turbine	4 x 10 kW	**5** x 10 kW	BWC Excel-S Bergey

These configurations will be used in the rest of the analysis and will be compared to the baseline (existing) configuration using a 150 kW diesel engine.

Storage tank data

Ideal operating conditions include an infinite storage in the sense that there are no volumetric and energetic constraints related to the storage of compressed air and its use, among other conditions. The operation scenario is based on the following assumptions:

- The volume of the tank is "infinite." Tank size is such that the system can store excess energy at all times, with no volumetric and energetic constraints. Storage system parameters, i.e. storage pressure and autonomy are chosen accordingly.
- The minimum allowable power for storage is zero. That means that any excess power is used for storage or, in other words, the power dissipated by the system is zero.
- The number of compressor stages must be the highest possible to improve the compression performance.
- The compression is done under the following conditions: pressure of the outdoor air (1 bar), storage temperature (20 ° C) and the polytropic exponent of air (n = 1,3).

Based on these assumptions, the ideal scenario used for this study is presented in this Table.

After a technical study conducted with a specific software for WDCAS technology, the optimal configuration is as follows.

Table 31: Characteristics of the storage system

Number of compressor stages	5
Polytropic exponent	1,3
Atmospheric pressure	1 bar
Storage temperature	20°C
Polytropic efficiency	80%
Compressor motor efficiency	90%
Minimum allowable power for storage	5 kW
Storage pressure	30 bars
Number of days of autonomy	1000 (infinite tank volume)

<u>Operation results and WDCAS system performance</u>

The WDCAS software provides the fuel consumption, the number of hours of operation and the dissipated power for the following diesel only and WDCAS configurations. The figure below summarizes these results for WPPR=65% and WPPR=100%.

Results	
Minimal load	13,80 kw
Average load	25,36 kw
Maximal load	47,70 kw
Average wind speed	4,78 m/s
150 Kw Diesel Only consumption	112420 L

Commentaire [AI10]: It is not possible to have as an assumption that the volume is infinite and at the end (Table 2) to have only 1 day autonomy!

Commentaire [Y11]: OK

Commentaire [AI12]: Faut donner plus de détails et citer une référence. Expliquer les bases de la méthodologie utilisée pour déterminer cette configuration.

Commentaire [Y13]: J'ai ajouté la méthodologie

Commentaire [AI14]: A compléter pour expliquer comment sont faits les calculs pour les autres configurations, diesel seulement, éolien-diesel etc. Tu dois mieux introduire ces informations qui ne sont pas du tout expliquées ici.

Commentaire [Y15]: OK

WDCAS consumption WPPR=65%	35917 L
WDCAS consumption WPPR=100%	33851 L

Generator operating hours at 30% of his nominal power	
WDCAS	
Supercharged WPPR=65%	780 h
no supercharged WPPR=65%	795 h
Supercharged WPPR=100%	841 h
no supercharged WPPR=100%	779 h
150 Kw Diesel Only	
no supercharged	5046 h

Dissipated Power	
150 Kw Diesel Only	101083 kW
WDCAS for WPPR=65%	1352 kW
WDCAS for WPPR=100%	1594 kW

Figure 18: Power balance of WDCAS for WPPR=65% and WPPR=100%

Commentaire [AI16]: Attention, ce sont des kWh qui sont dissipés, pas des kW

Commentaire [Y17]: Le logiciel produit la dissipated power (Kw) !

Commentaire [AI18]: À rajouter les résultats pour WPPR=100% dans le même tableau

Commentaire [Y19]: OK

WDCAS provides a significant fuel economy, precisely 76 503 L for a WPPR=65% and 78 569 L for a WPPR=100% per year compared to the baseline configuration with a 150 KW diesel generator. The number of hours when the diesel is operating at less than 30% of its nominal power is also reduced significantly. Finally, the dissipated energy is significantly lower with the WDCAS system.

The system with a WPPR=100% doesn't provide a higher technical gain for the increase in wind turbine number. As shown in the table below, less than 10% gain is provided for the diesel consumption, supercharged and not supercharged diesel engine hours. This could be explained by the fact that the wind speed on this site is not powerful enough to scale up with the number of wind turbines. Finally, the dissipated power is low (about 18%) for the number of wind turbines due to the low decrease of in supercharged and not supercharged hours.

Table 32: Difference in power balance of WDCAS for WPPR=65% and WPPR=100%

	WPPR = 65%	**WPPR = 100%**	**Difference**
WDCAS diesel consumption (L)	35917	33850,9	6%
Supercharged hours	780	841	8%
No supercharged hours	795	779	2%
Dissipated WDCAS power (Kw)	1352	1593,623	18%

The next graph shows the operation frequency of WDCAS diesel generators, we see that one generator works for 78% of the time in order to cover the average load consumption in the case of a WPPR=65% and 77,5% for a WPPR=100%. As a result, not much of a difference exists between the two systems.

The two generators operate together only during periods of peak demand when wind energy is not available. For security purposes, it is recommended to have a backup generator of similar power.

Commentaire [AI20]: A rajouter les résultats pour WPPR=100% et ajuster le texte en conséquence

Commentaire [Y21]: OK

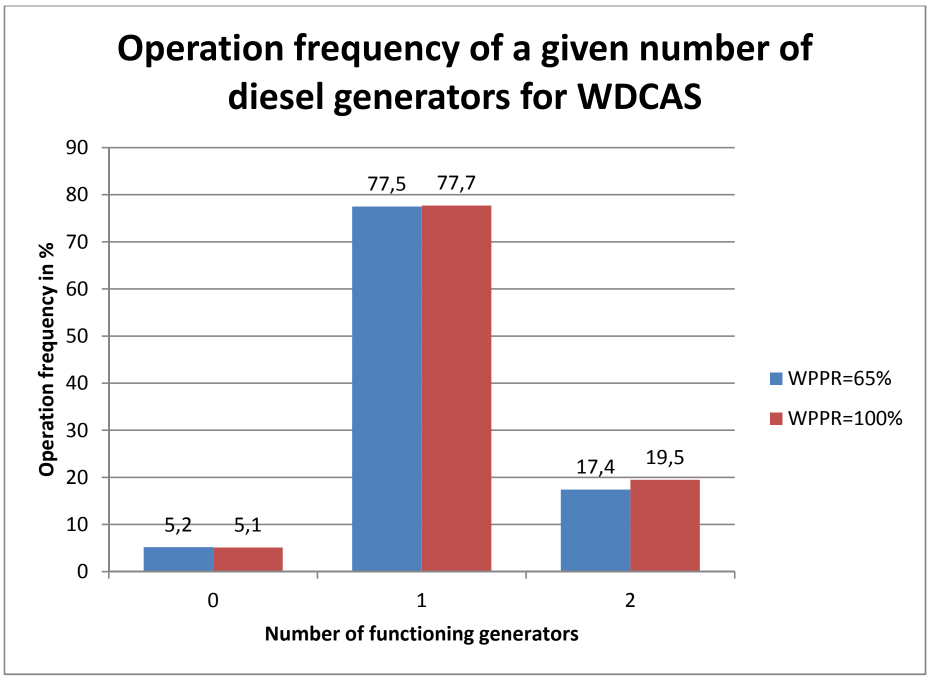

Figure 19 : Operation frequency of WDCAS diesel generators for WPPR=65% and WPPR=100%

Finally, the WDCAS system is able to provide required power and energy to the charge during the whole period of operation. Fuel economy and reduction of diesel operating hours are significant regardless of the WPPR.

Commentaire [AI22]: L'analyse financière n'est pas encore faite. Comment tu peux tirer cette conclusion ?

As a conclusion of the technical analysis, the increase in wind turbines doesn't create a significant change in the outputs. Although the technical study is completed and presents disadvantageous results for the WPPR increase, it is necessary to conduct a financial and environmental analysis to complete the project analysis. In the next section we will evaluate the financial and risk parameters associated with WDCAS operation.

Commentaire [AI23]: L'analyse financière n'est pas encore faite. Comment tu peux tirer cette conclusion ?

Commentaire [Y24]: Ok

Financial analysis

Cost Data

In order to determine the profitability of the system, it is required to introduce the cost data of its components. The following data summarizes the costs used in the financial simulation for the WDCAS system. We will start to present our costs by stating the fuel cost and the fuel economy, the machine cost and the equipment's.

Fuel Cost and fuel economy:

The fuel economy is the amount of fuel saved by using the WDCAS and is presented in Table 4 for WPPR=65% and WPPR=100%.

Table 33: General Cost and fuel economy for WPPR=65% and WPPR=100%

	WPPR = 65%	WPPR = 100%	Difference
Fuel Cost	89 792,50 $	84 627,26 $	6%
Annual Fuel economy	191 257,50 $	196 422,74 $	3%

The total cost of fuel and its economy is the number of liters consumed or saved at a price of 2,5 $/L. This price is higher due to the indexed transportation price because of the remoteness of the site.

We can clearly see the total fuel cost decreased by less than 10 %. Which is not a huge change for the cost of one more wind turbine.

Cost of equipment

Diesel Generator

The power requirement of the diesel engine is previously computed by the WDCAS software, the results are stated in the Wind-Diesel system configuration section.

Table 34: Diesel Generator costs

Diesel Generator	Amount (WPPR=65%)	Amount (WPPR=100%)	Difference
Initial Capital	37 800,00 $	37 800,00 $	0,00%
Financial depreciation	15 057,00 $	15 034,32 $	0,15%
Operation and maintenance	2 258,55 $	2 255,15 $	0,15%

The diesel generator total cost estimation is based on what is available in the market [27]. The lifespan is measured in hours, so the annual financial deprecation will be the initial cost multiplied

Commentaire [AI25]: A rajouter pour le 100% dans le même tableau

Commentaire [Y26]: Fait!

Commentaire [AI27]: Quelle est la raison d'avoir choisi un montant de 2.5$/l, tu dois mieux le justifier (données disponible de la part de l'opérateur ?). Aussi, les hypothèses utilisées comme le coût unitaire du combustible doivent être introduites AVANT de faire les calculs, en occurrence expliquer l'hypothèse avant de mettre le tableau avec le calcul.

by the annual usage ratio i.e. the annual operating hours divided by the lifespan. The life span of a diesel engine is 15 000 hours [28]. The maintenance cost is 0,001% of the initial cost per hour of functioning [28]. The total O&M cost is the last rate times the hours of using the diesel engine. Note that the O&M and the replacement cost are yearly computed. The difference in the financial depreciation is not significant to justify the added wind turbine in WPPR=100% for this equipment's cost.

Commentaire [AI28]: Do you have a reference, web site of manufacturer or something. It will be much better to add a reference or explain where from these figures are coming.

Commentaire [Y29]: See Below

Commentaire [AI30]: Pourquoi tu mélanges ici les données du diesel avec celles des éoliennes.

Commentaire [Y31]: Typo

Wind Turbines

The wind turbine sizing is also computed by the WDCAS software, according to the wind profile, the geographical location and the electrical demand. The results are also presented in the Wind-Diesel system configuration section.

Table 35: Wind Turbine costs for WPPR=65% and WPPR=100%

Commentaire [AI32]: A rajouter les valeurs pour WPPT=100%

Commentaire [Y33]: OK

Wind Turbine	WPPR = 65%	WPPR = 100%	Difference
Total Capital	400 000,00 $	500 000,00 $	25%
Financial depreciation	26 666,67 $	33 333,33 $	25%
Operation and maintenance	1 200,00 $	1 500,00 $	25%

The total cost of the wind turbines is actually high because of the transportation cost of the tower and its cost itself [29]. The lifetime of the wind turbine is estimated to 15 years [28], therefore the depreciation is the total cost divided by the lifetime. Finally, the O&M cost is estimated to 3% of the initial cost [28].

Compressed air storage system:

The compressed air storage system is sized by the WDCAS software, according to the compressed air demand from the diesel engine. These values are the same chosen to size the WDCAS power plant in the Wind Energy TechnoCentre in Gaspé, Québec.

Table 36: Compressed air storage system costs for WPPR=65% and WPPR100%

Commentaire [AI34]: A rajouter les valeurs pour WPPT=100%

Commentaire [Y35]: OK

Compressed air storage system	Quantity	Amount for WPPR= 65% and 100%
Storage System	5,4 m^3	270 000,00 $
Compressor	37 Kw	17 000,00 $
Control Room	1	35 000,00 $
Operation and maintenance	1	2 870,00 $

The Control room is the room where all the control equipment is installed, including the total price of the building and the control equipment. The compressed air storage system is composed mainly of the storage system and the compressor. The storage system consist of the valves, thermal regulation system, and the reservoir. The firm that designed the compressed air storage system estimated the price to 50 000 $\$/m^3$. The compressor's price is estimated according to the market price. Finally, the O&M is estimated to 1% of the total initial cost. The lifetime of the storage system is estimated to 20 years. In this simulation the storage system will be paid totally in the beginning of the project.

Cost Summary:

The following table is a summary of all the main costs: initial costs, the annual fees and the annual economies. The annual fees are the depreciation, the O&M and the exploitation cost (fuel). Finally, the annual economies are viewed as revenue for future financial computations, sensitivity analysis and risk analysis.

Table 37: Cost Summary for WPPR=65% and WPPR=100%

	WPPR = 65%	WPPR = 100%	Difference
Initial Capital	322 000,00 $	322 000,00 $	0%
Financial depreciation	41 723,67 $	48 367,65 $	16%
Operation and maintenance	6 328,55 $	6 625,15 $	5%
Exploitation cost	89 792,50 $	84 627,26 $	6%
Annual fees	137 844,72 $	139 620,06 $	1%
Annual Economy	191 257,50 $	196 422,74 $	3%

The initial capital is the same because it is chosen to purchase the storage system in the beginning of the project. The financial depreciation has seen an increase close to 16% because of the added wind turbine and the slight increase in the depreciation of the diesel engines. The O&M is increased by 5% because the O&M of the diesel engines is higher compared to the one of the wind turbine. The exploitation cost dropped by 6% because of the lower fuel consumption. Finally, the annual fees slightly dropped (1%) and the annual savings increased because of the slight drop in fuel consumption.

Financial Analysis

Discounted cash flow:

The discount rate is usually viewed as the inflation rate added to the risk rate, it can also be viewed as a certain percentage of profit that the project managers decide. For this project we choose 10%. The fuel index rate is estimated to 5%. The following chart and graph are a representation of the yearly discounted cash flow during the overall lifetime of the project.

Table 38: Discounted cash flow table

Commentaire [AI36]: IL faut présenter ces résultats en même temps que ceux du cash flow. A mettre ensemble discount rate avec indexed cash flow and WPPT=100%

Commentaire [Y37]: OK

Year	WPPR = 65%	WPPR = 100%	Difference
1	50 984,93 $	54 220,74 $	6%
2	48 667,43 $	51 756,16 $	6%
3	46 455,28 $	49 403,61 $	6%
4	44 343,67 $	47 157,99 $	6%
5	42 328,05 $	45 014,45 $	6%
6	40 404,05 $	42 968,33 $	6%
7	38 567,50 $	41 015,23 $	6%
8	36 814,43 $	39 150,90 $	6%
9	35 141,05 $	37 371,31 $	6%
10	33 543,73 $	35 672,62 $	6%
11	32 019,01 $	34 051,14 $	6%
12	30 563,60 $	32 503,36 $	6%
13	29 174,35 $	31 025,93 $	6%
14	27 848,24 $	29 615,66 $	6%
15	26 582,41 $	28 269,50 $	6%
16	25 374,12 $	26 984,52 $	6%
17	24 220,75 $	25 757,95 $	6%
18	23 119,81 $	24 587,13 $	6%
19	22 068,91 $	23 469,54 $	6%
20	21 065,78 $	22 402,74 $	6%

Lastly, the following graph is showing the decreasing discounted cash flow since each year 10% is retained as profit according to the discount rate. It is important to understand that the difference of 6% is due to the difference in the cash flow not the one in the index rate, since the latter is the same for both calculations. This difference is a result of the variability in the parameters stated in the previous section.

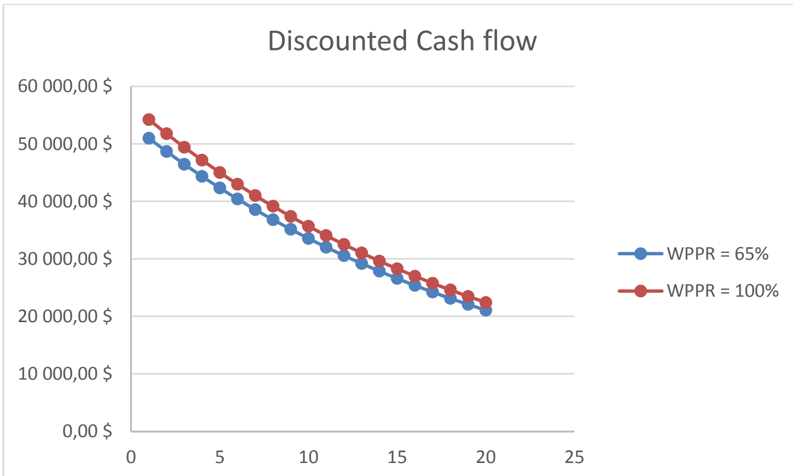

Figure 20: Discounted cash flow chart for both WPPRs

It is concluded that the system with a WPPR of 100% is more profitable than the one with a WPPR of 65%, the increase is 5% in cash flow. Both WPPRs offer an interesting cash flow remaining positive through the project lifetime. At stage we can have an idea of the profitability of the system.

<u>Financial parameters:</u>

In the following chart is a summary of all the financial parameters for the implementation of WDCAS system at Esker camp for both configurations (WPPR=65% and WPPR=100%).

Table 39: Financial parameters summary for WPPR=65% and WPPR=100%

Commentaire [AI38]: A rajouter les résultats pour WPPT=100%

Commentaire [Y39]: C'est WPPR pas WPPT

	WPPR = 65%	WPPR = 100%	Difference
Net Present Value	357 287,13 $	400 398,80 $	12%
Internal rate of return	21%	23%	6%
Profitability Index	2,11	2,24	6%
Discounted Payback	7,88	7,38	6%
Annual produced energy	222153,60 Kwh	222153,60 Kwh	0%
Produced energy during 20 years	4443072,00 Kwh	4443072,00 Kwh	0%
Net Present Cost	1 475 060,04 $	1 489 910,63 $	1%
Energy cost	0,78 $/Kwh	0,79 $/Kwh	1%

The net present value is the total discounted cash flow. The internal rate of return is the maximum discount rate for the project to stay profitable and is larger than the discount rate of 10%.

The profitability index describes the efficiency of the project, it is the outflow divided by the inflow. For the Esker project, this index is superior to one that mean that the overall profit is superior to the overall expenses, therefore the project is profitable.

The WPPR=100% NPV increase by 12% because of the higher annual saving. As a result the profitability index is higher. The same reason is the cause of the increase in the IRR.

The payback is the number of years required to pay all the expenses of the project and to start making positive cash flow. The discounted payback is the duration needed for the project to start making positive discounted cash flow. As shown before the WPPR=100% cash flow is higher thus it is shown in the lower discounted payback as well.

The Net Present Cost (NPC) is the total discounted outflow, it is used to compute the energy cost. The latter is defined as the net present cost divided by the total discounted energy produced during the life time of the project, the discount rate is the same used in both the energy and the cash flow. In this case the energy cost is less than one dollar, as it will be proved in future sections this amount is very competitive compared to the actual energy cost using only diesel engines.

Commentaire [AI40]: SI c'est cette valeur que tu utilises pour calculer le COE TU DOIS ENLEVER LES COÛTS DE REMPLACEMENT DES ÉQUIPEMENTS puisque ces coûts sont déjà pris en compte dans l'investissement initial. Au plus, tu dois rajouter un coût de remplacement des éoliennes après 15 ans et du diesel lorsque la vie utile est finie.

Commentaire [Y41]: Je ne suis pas sûre de ton point. La documentation de HOMER affirme l'utilisation du coût de remplacement dans le NPC et par suite dans le COE.

The WPPR=100% NPC is higher because of the added cost of the wind turbine's O&M and depreciation. Since the WPPR=100% NPC is higher, for the same energy produced there is the same difference and the WPPR=100% COE is slightly higher.

Table 40: COE comparison of WDCAS (WPPR=65% and WPPR=100%) with baseline scenario

	WPPR = 65%	WPPR = 100%	Difference
Diesel Engine Only	1,2725 $/Kwh	1,2725 $/Kwh	-
WDCAS	0,7799 $/Kwh	0,7878 $/Kwh	1%
Difference	39%	38%	2%

The chart proves that using WDCAS technology, we reduce the energy cost by 38-39%, and this is mainly due to the fact that we use less fuel.

Environmental analysis; GHG reduction analysis

In this section, we analyze the environmental impact replacing the diesel engine with WDCAS technology. The information is summarized in the chart below.

Table 41: Environment impact of using WDCAS (WPPR=65% and WPPR=100%)

	Energy (Kwh)	Tons of CO2 Produced	Difference
Diesel Only	134771,30	34,1	-
WDCAS WPPR=65%	107518,59	27,2	20%

WDCAS WPPR=100%	102178,29	25,9	24%

The use of WDCAS results in 20% (WPPR=65%) and 24% (WPPR=100%) reduction of GHG emissions compared with baseline scenario.

Risk analysis:

In this section a risk analysis will be completed to assess the accuracy of the analysis. The risk analysis is made on the net present value, the internal rate of return, the profitability index and the payback, both for WPPR=65% and WPPR=100%. A risk rate of 15% is used in all the simulations.

Risk analysis for net present value:

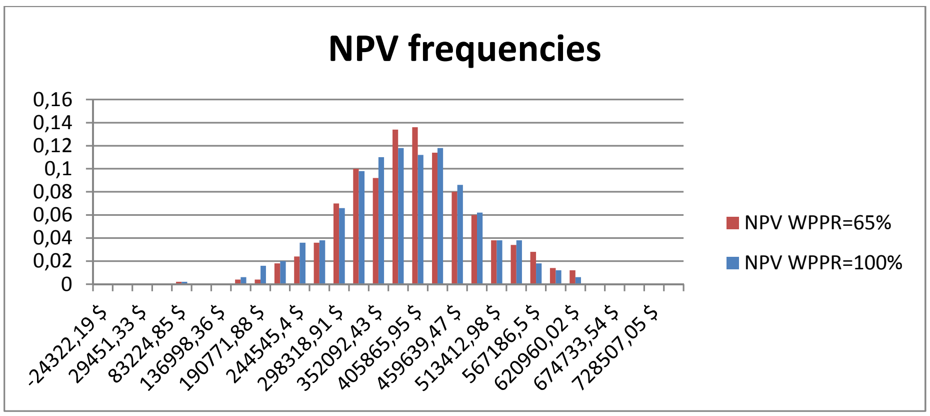

Figure 21: NPV frequency chart (WPPR=65% and WPPR=100%)

The frequency of the NPV above is in good coordination with the results of the financial analysis, the most frequent value is close to the average and the median.

Table 42: Statistics for NPV (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Median	354 795,84 $	411 242,60 $	16%
Inferior limit of confidence interval	236 846,46 $	274 152,16 $	16%
Superior limit of confidence interval	493 761,27 $	543 686,88 $	10%
Average	357 518,05 $	409 251,72 $	14%

For a risk rate of 15%, the median is also close the actual NPV in both WPPRs, finally the confidence interval contains the computed NPV as predicted.

The average difference in the results is close to 12%, it is the same difference in the previous section for the NPV. Therefore the resulted difference in the risk analysis is borrowed from the financial analysis.

Risk analysis for the internal rate of return:

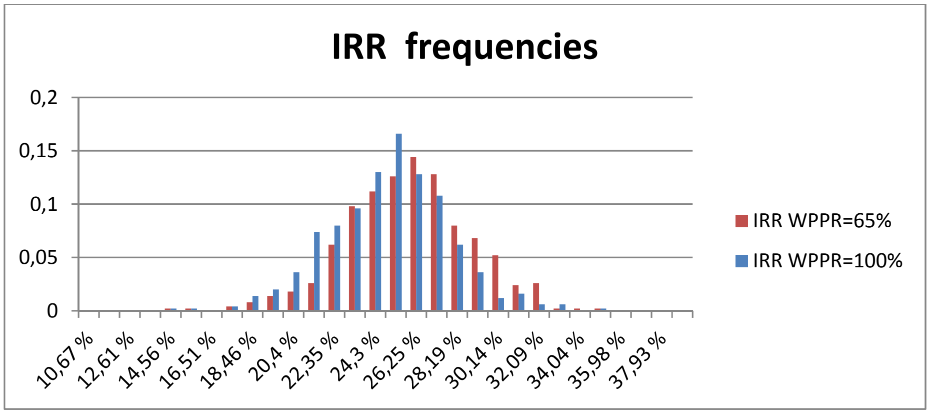

Figure 22: IRR frequency chart (WPPR=65% and WPPR=100%)

For the internal rate of return, the most frequent value is close to the computed value calculated in the financial analysis.

Table 43: Statistics for IRR (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Median	22,34%	23,56%	5%
Inferior limit of confidence interval	18,25%	19,39%	6%
Superior limit of confidence interval	26,56%	27,36%	3%
Average	22,28%	23,43%	5%

The confidence interval contains the computed IRR as predicted for a risk rate of 15%. Finally, the median and the average is also close the actual IRR in both WPPRs.

The average difference in the results is close to 6%, it is the same variability previously computed. Therefore this discrepancy in the risk analysis is a result of the one in the financial analysis.

Risk analysis for the payback:

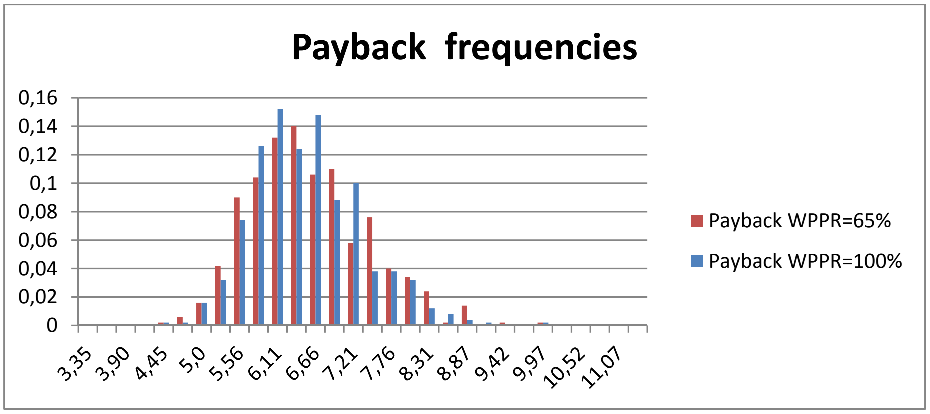

Figure 23: Payback frequency chart (WPPR=65% and WPPR=100%)

According to this graph the most frequent value and the average payback is close the computed value in the financial analysis.

Table 44: Statistics for the payback (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Median	6,03	5,71	5%
Inferior limit of confidence interval	5,06	4,80	5%
Superior limit of confidence interval	7,51	7,05	6%
Average	6,15	5,78	6%

For a risk rate of 15%, the confidence interval contains the computed payback as predicted. Finally, the median is also close the actual payback in both WPPRs.

The average difference in the results is close to 6%, it is the same variability previously computed. Therefore the resulted difference in the risk analysis is borrowed from the financial analysis.

Risk analysis for the profitability index:

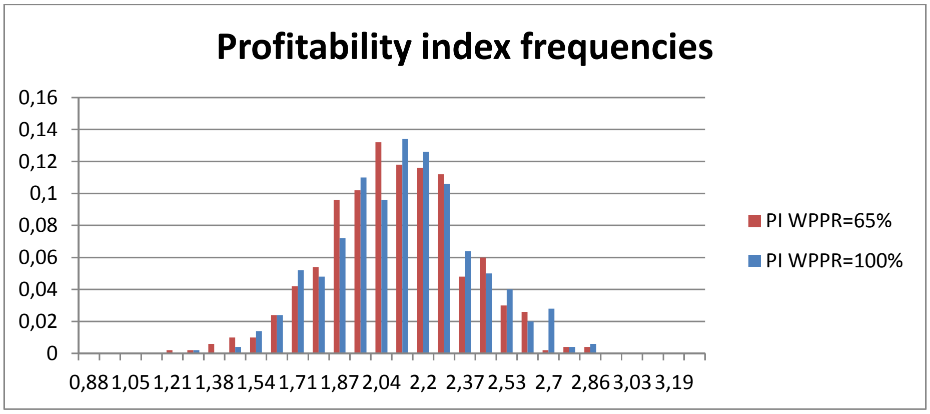

Figure 24: PI frequency chart (WPPR=65% and WPPR=100%)

From the graph, the expected PI matches closely the most frequent value.

Table 45: Statistics for Profitability index (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Median	1,97	2,08	6%
Inferior limit of confidence interval	1,59	1,69	6%
Superior limit of confidence interval	2,35	2,50	7%
Average	1,97	2,09	6%

The table above presents the average and the median of the PI for both WPPRs. These values are close to the expected value and the latter is bounded by the confidence interval found above for a 15% risk rate.

The average difference in the results is close to 6%, it is the same variability previously computed. Therefore this discrepancy in the risk analysis is a result of the one in the financial analysis.

Sensitivity Analysis:

The sensitivity analysis is the analysis of which parameter is the most influent for the variation of the financial parameters. The latter will be made on the net present value, the internal rate of return, the profitability index and the payback.

Sensitivity analysis for net present value:

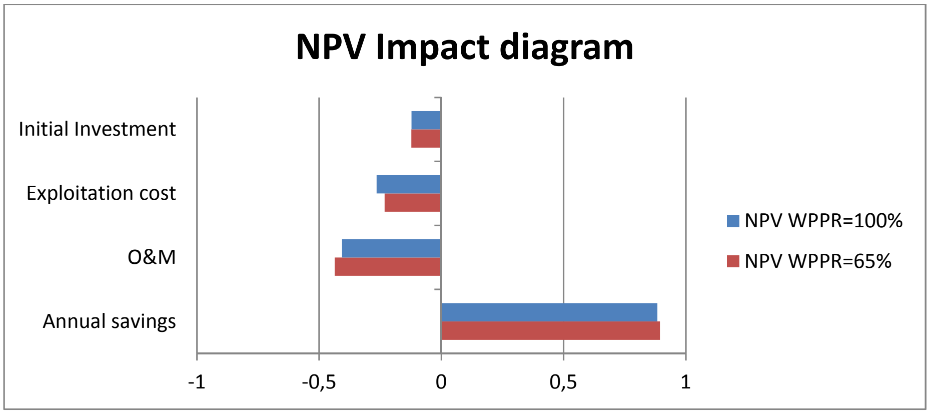

Figure 25: Impact diagram for the NPV chart (WPPR=65% and WPPR=100%)

Table 46: Impact percentage for NPV (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Initial Investment	-12%	-12%	1%
Exploitation cost	-23%	-26%	14%
O&M	-44%	-41%	7%
Annual savings	89%	88%	1%

The impact diagram produced from the software indicates that the most influent factors in order are annual economy, O&M, initial investment and the exploitation cost. For that reason we suggest that we use less fuel by increasing the energy efficiency of the camp, this will reduce the exploitation cost and increase the annual fuel economies, then we can for example apply a more intelligent O&M using neural network predictions or any type of prediction systems.

It is clear the rank of the impact stays the same in this chart for the NPV. The difference translates the effect of the added wind turbine for the WPPRs.

<u>Sensitivity analysis for the internal rate of return:</u>

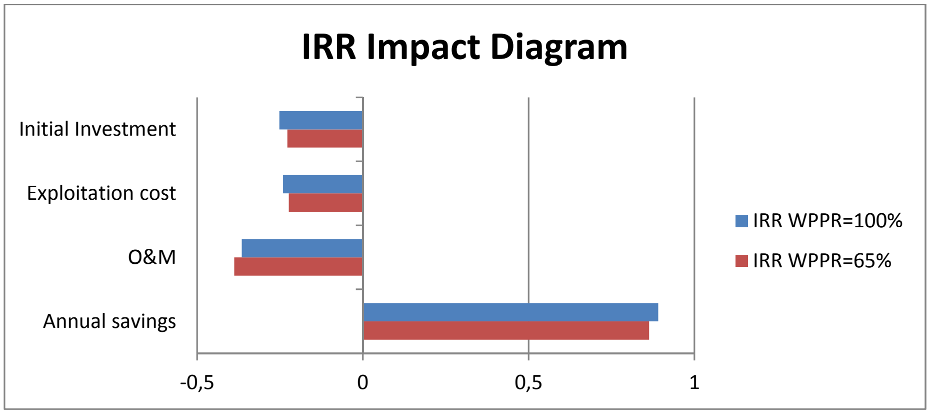

Figure 26: Impact diagram for IRR (WPPR=65% and WPPR=100%)

Table 47: Impact percentage for IRR (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Initial Investment	-23%	-25%	11%
Exploitation cost	-22%	-24%	8%
O&M	-39%	-37%	6%
Annual savings	86%	89%	3%

Like before, the generated impact diagram indicates that the most influent factors in order are annual economy, O&M, initial investment and the exploitation cost. Since the influences are the same as the NPV's we suggest the same recommendations.

The discrepancy is extremely low for both WPPRs and the rank remains the same.

Sensitivity analysis for the payback:

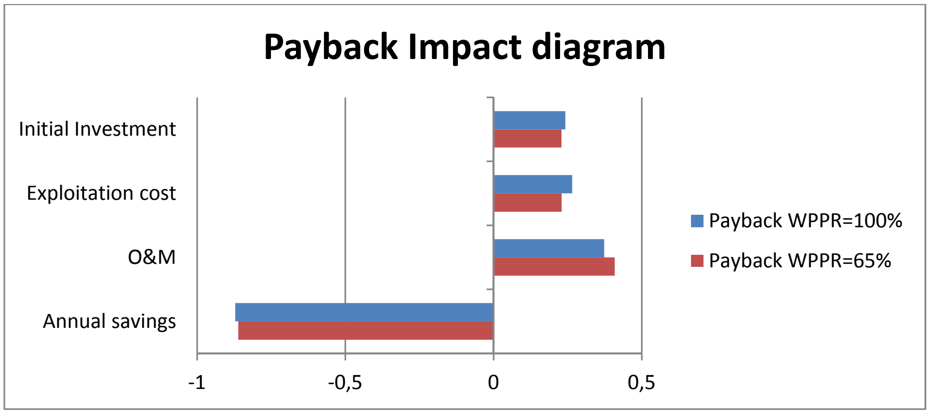

Figure 27: Impact diagram for Payback (WPPR=65% and WPPR=100%)

Table 48: Impact percentage for Payback (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Initial Investment	23%	24%	6%
Exploitation cost	23%	27%	15%
O&M	41%	37%	9%
Annual savings	-86%	-87%	1%

The created impact diagram provides the most influent factors in the following order: annual economy, O&M, initial investment and the exploitation cost. Since the influences are the same as the NPV's and IRR's we suggest the same recommendations.

The rank of the impact remains unchanged in this chart for the payback. The difference translates the effect of the added wind turbine in the initial investment and the fuel consumption for the O&M with exploitation cost.

Sensitivity analysis for the profitability index:

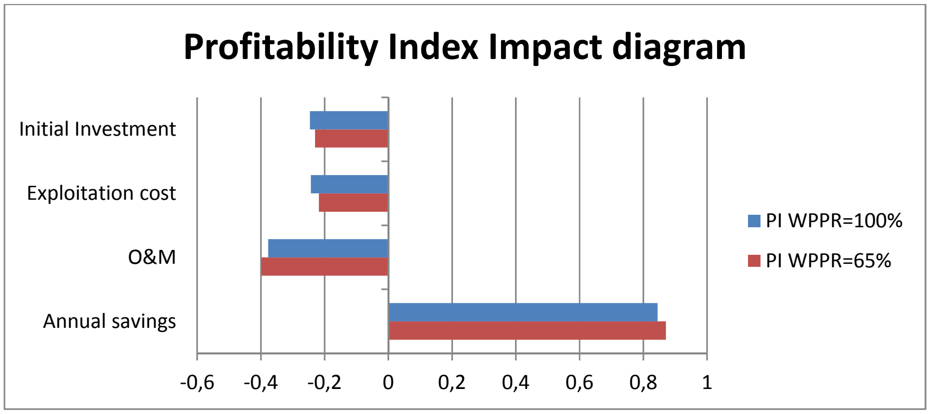

Figure 28: Impact diagram for PI (WPPR=65% and WPPR=100%)

Table 49: Impact percentage for PI (WPPR=65% and WPPR=100%)

	WPPR = 65%	WPPR = 100%	Difference
Initial Investment	-23%	-25%	7%
Exploitation cost	-22%	-24%	12%
O&M	-40%	-38%	5%
Annual savings	87%	85%	3%

Finally, the impact diagram easily offers the most influent factors in the same order as before: annual economy, O&M, initial investment and the exploitation cost. Since the influences are the same as the NPV's and IRR's and the payback we suggest the same recommendations.

The rank of the impact stays the same in this chart for the profitability index. The difference is explained by the low diesel consumption and the wind turbine's initial investment.

Conclusion:

This study has shown that the installation of a wind-diesel hybrid system with compressed air storage for the Esker camp is clearly a financially feasible solution, and a very profitable project. The analysis of various financial parameters used in project management increases the accuracy of the study in favor of the profitability of the project.

The WDCAS system has also proved to be environment friendly, by using less fuel, allowing this to become also a good financial solution for the Esker camp. The high WPPR has proven to be the most profitable solution for the system. The high WPPR of 65% has proven to be less profitable than the one with a WPPR of 100%. It is mainly due the fact that the added wind turbine increases the cash flow and this slight technical improvement improves the profitability of the project. As result the high WPPR system is the recommended.

The future work in this project will be the analysis in the field of the estimated values worked in this study and comparing it with the real costs concerning the energy, finances and the environment.

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CHAPITRE 4
CONCLUSION GÉNÉRALE

4.1 SYNTHESE DES RESULTATS OBTENUS AU COURS DE MON ETUDE

4.2.1. Description du logiciel développé pour le calcul de rentabilité d'un SHEDAC

La première phase du présent projet de recherche a été de rechercher un modèle et de développer un logiciel innovateur permettant l'analyse financière, de sensibilité de risque et d'analyse écologique d'un système éolien-diesel avec stockage par air comprimé (SHEDAC).

Une revue de littérature a été menée afin de déterminer les différents modèles qui serviront à la conception du logiciel. Ces modèles incluent les différentes formules et équations qui seront utilisées pour les analyses que réalise le logiciel.

Ainsi, grâce aux entrées économiques qui y ont été implantées, le logiciel permet de rentrer différents coûts pour faire une simulation financière. Les résultats obtenus proposent des informations sur la valeur actuelle nette, le taux de rendement interne, l'indice de rentabilité, le délai de récupération et le coût de l'énergie.

Ces données ont été introduites dans un modèle d'analyse de sensibilité afin de présenter l'influence de chaque paramètre d'entrée sur les sorties à savoir la valeur actuelle nette, le taux de rendement interne, l'indice de rentabilité et le délai de récupération.

Ensuite, un modèle d'analyse de risque qui est similaire à l'analyse de sensibilité, sauf que le changement dans les paramètres d'entrée suit une loi de probabilité et le calcul est répété un grand nombre de fois pour avoir des résultats précis.

Enfin, l'analyse écologique ou l'étude d'impact environnemental, reprend certaines données techniques, en particulier l'énergie produite par les génératrices diesel, et les intègrent dans une formule pour obtenir les émissions de CO2 du système.

La véracité des résultats générés par le logiciel a également été vérifiée grâce à une comparaison avec le logiciel HOMER© et RETScreen, deux références dans le marché des logiciels de dimensionnement de systèmes hybrides. Avec des écarts entre les résultats inférieurs à 10%, la fiabilité de l'outil développé a pu, facilement, être attestée, de même que de la pertinence des conclusions que l'on peut en tirer.

4.2.2. Analyse de rentabilité d'un SHEDAC pour son implantation sur le site d'Esker

Après que le logiciel de calcul de rentabilité d'un SHEDAC a été conçu et a été validé, il est pertinent de l'appliquer sur un projet concret. Le projet sélectionné pour l'application du logiciel est celui de l'étude de faisabilité d'un SHEDAC du camp Esker.

Une première étude technique a démontré la consommation non efficace des sources électrique impliquant l'utilisation d'équipements énergivores. Une liste de recommandations a été présentée lors d'une précédente étude pour améliorer l'efficacité.

Une fois la nouvelle consommation du camp Esker, une étude précise pour le dimensionnement d'un SHEDAC sur le site a été réalisée. Ce travail avait pour objectif principal de mettre en place un système optimal, d'un point de vue technique et énergétique, afin de répondre aux problématiques et contraintes du camp.

À l'issue de cette étude, la configuration optimale qui en est ressortie est un système composé de deux génératrices Caterpillar de 27 kW, de quatre éoliennes Bergey de 10 kW, et d'un système de stockage dont la pression est de 30 bars. Le SHEDAC ainsi dimensionné permet de proposer une économie de carburant de près de 70 % par rapport au système actuellement en place.

Une fois l'étude technique terminée, l'étude de rentabilité financière a pu débuter. L'étude de rentabilité financière et écologique à prouver que le SHEDAC est solution rentable avec un impact mineur sur l'environnement, pour le camp Esker. Deux cas ont été comparés, un avec haute pénétration éolienne (100%) et un autre avec faible pénétration éolienne (65%). Les deux cas avaient des performances similaires au niveau technique. Une petite différence est remarquée au niveau de la consommation et l'économie en carburant (4.5%).

Les coûts des systèmes diesel dans les deux cas sont similaires, leurs coûts de remplacement et coûts d'opération et maintenances sont similaires aussi. En ce qui concerne les éoliennes, le système avec une haute pénétration éolienne comprend une augmentation de coût de 25% dû à l'ajout d'une éolienne supplémentaire. Le remplacement et la maintenance relatifs à cet ajout sont amplifiés du même pourcentage. Les coûts relatifs au système de stockage d'air comprimé restent semblables, car le même dimensionnement est utilisé dans les deux cas.

Durant l'analyse financière, il est démontré que tout le flux monétaire du SHEDAC avec une TPE de 100% est 6% plus grand que celui d'un faible TPE. Cette différence se répercute sur tous les résultats financiers. La valeur actuelle nette du système à haute pénétration est de 12% plus importante que dans le cas adverse. Ceci prouve la rentabilité du SHEDAC à 100% de TPP.

De plus, la solution à haute pénétration éolienne présente une baisse de 4% d'émission en CO_2 comparée à la solution alternative. Dans les deux cas, l'analyse de risque est conforme au résultat prédit par l'analyse financière. Enfin, l'analyse de sensibilité prouve dans les deux cas que l'économie annuelle influence en majorité les paramètres financiers.

En conclusion, le SHEDAC représente une solution rentable pour le cas du camp Esker, il est important de noter que le SHEDAC à haute pénétration éolienne (100%) est préféré, car il présente des performances financière et écologique intéressantes comparées à celui à basse pénétration éolienne.

4.2 CONCLUSIONS ET PERSPECTIVES

Ce mémoire fait suite à une série de travaux dans lesquels il a été démontré, pour diverses situations, l'efficacité d'un système hybride éolien-diesel avec stockage par air comprimé (SHEDAC) destiné à alimenter en électricité des sites isolés. À travers ce projet, a été, ainsi, modélisé, mis en œuvre et validé, un logiciel d'analyse de rentabilité financière, d'analyse de sensibilité et de risque, ainsi que d'étude d'impact écologique pour un SHEDAC. Le développement de cet outil s'est présenté comme une innovation dans le domaine puisque, à ce jour, il n'existait pas de logiciels capables de modéliser un tel système.

En proposant plusieurs types d'analyses, à savoir une analyse financière, analyse de sensibilité et de risque, ainsi qu'une analyse écologique le logiciel permet de rechercher des solutions optimales pour l'implantation d'un SHEDAC en zone isolée.

Ce mémoire étant présenté dans un projet de recherche global visant l'implantation d'un SHEDAC sur le site isolé du camp Esker, il a été possible de mettre en application l'utilisation du logiciel développé afin de proposer un système rentable et écologique répondant aux problématiques énergétiques du camp.

En ce qui concerne le logiciel, il sera nécessaire d'implémenter le module énergétique afin de proposer un outil complet et semblable à ceux disponibles sur le marché. Une autre action préconisée à l'égard de l'amélioration et l'utilisation du logiciel est de réaliser une validation expérimentale des résultats obtenus avec le logiciel. Le banc d'essai du TechnoCentre éolien pourrait réaliser une telle validation.

Au sujet de l'implantation du SHEDAC sur le site d'Esker, diverses actions pratiques devront être réalisées. D'une part, des études sur la viabilité des paramètres techniques d'analyse (vitesse de vent, consommation électrique). D'autre part, des actions concrètes sur la réduction de la consommation énergétique actuelle du camp devront être apportées. Il est aussi important de définir et réaliser des systèmes de supervision et de contrôle appropriés pour le bon fonctionnement et la bonne gestion du SHEDAC sur le site.

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