# Optimal design and control of wind-diesel hybrid energy systems for remote Arctic mines

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**Abstract**

Mining operations are located in increasingly remote areas to search for relatively high grade mineral deposits, despite the challenges that arise. These challenges are fundamentally logistic and directly impact the profitability of the remote operation. One of the main challenges is energy supply, since locations that lack of a power grid, fuel pipelines or adequate – if existing – road access, have substantially increased energy-related operating costs. Today, a remote mine’s energy costs add up to 40% of total operating expenses; this is in contrast with grid connected, accessible mines, where energy costs seldom reach 20%. In searching for more cost effective energy supply options, the present work uses the Optimal Mine Site Energy Supply (OMSES) concept to optimize the design and operation schedule of a remote underground mine’s energy supply system. Energy demand, weather, and economic data were collected and processed, emulating a remote mine in the Northwest Territories, Canada. The optimal energy system minimized the total cost of the energy supply, which included not only the operation cost, but also the annuitized capital investment in equipment. Subsequently, the optimal system’s design for the considered demands and environmental factors was subject to simulation and control optimization. Wind power was included in the formulation. Issues such as the necessary spinning reserve, and the penetration curtailment, among others, were analyzed, both in the design and the control problems.

The work identified potential improvement for the integrated design and control of a remote mine’s energy system, in particular when including a renewable energy resource with a considerable level of variability, i.e. wind. The optimal solution included the installation of two wind turbines, achieving 3% diesel savings with a 20% increase of investment compared with the conventional design. The model was validated with a real project – the Diavik Diamond Mine energy supply system, which included a wind farm with four turbines. A Model Predictive Control (MPC) approach was chosen to optimize scheduling in a simulation with variable conditions of wind speed and ambient temperature; this proved to be a convenient method to assess the robustness of optimal designs. Results also confirmed the limitations of design optimization when uncertainties related to wind energy were ignored.

**Keywords:** Mining; Wind power; Spinning reserve; Model Predictive Control

## 1. INTRODUCTION

The nature of a mineral deposit (grade, depth, geographic location) determines the practical minimal energy required to obtain the desired final product [1]. In turn, this influences the economic viability of resource extraction and processing; therefore ores that are cheaper to extract, both economically and energetically, are always first to be exploited [2]. This being said, the average ore grade of mined deposits has been steadily decreasing in the last century [1, 3]. This general trend is encouraged by the fact that newly discovered deposits are increasingly found in remote, difficult to access locations that lack infrastructure, and thus are associated with higher energy related costs.

Despite technological improvements, energy intensity (i.e. energy units per tonne extracted, hoisted, crushed, etc.) has been steadily increasing as a result of lower quality ores and deeper deposits [4]. This translates into higher costs of mineral extraction and processing. Thus, energy consumption is responsible for a significant share of the operating costs in mining. In Canada, between 10% and 30% of a mine's operation costs relate to energy inputs [4]. The numbers are even higher for remote mines that are not connected to the electric grid and generate their power on site by consuming fossil fuels, e.g. diesel. The urgent need in the mining industry to reduce energy consumption is changing the traditional mentality of an industry accustomed low energy costs relative to labor and capital.

Mainly due to these economic reasons, there has been a growing interest in designing optimized energy systems, also called Multi Energy Systems (MES), Distributed Multi Generation (DMG) and Distributed Energy Resources (DER) [5, 6]. Several software tools have emerged to solve for optimal energy supply system designs that ultimately address the economical problem of energy resources allocation [6]. The first attempt to optimize a mine energy system is found in [7], but this work, as well as those that use statistically-based demands (e.g. [8]), lack the robustness to manage uncertain operating conditions, whether they arise from the demand or the production side. Furthermore, the currently available methods seldom address improved or optimal design limitations to meet the final energy demands despite changes in the operating environment. This is one of the aims of the present work, i.e. to stress optimal energy design under changes in the operating conditions. For this purpose, the simulation of the system is performed under more realistic conditions, which provides an opportunity to evaluate the feasibility of the designs.

Among the approaches proposed to simulate and control dynamic systems in general and energy systems in particular, Model Predictive Control (MPC) provides several advantages. MPC is considered a system control approach characterized by its ability to: manage physical constraints, predict problem inputs, use simplified models of the real plant, and consider the cost functions suitable for optimization [9]. These features make MPC useful for energy scheduling optimization when simulating the operation of the system. Its use as an extension of OMSES, sharing the same mathematical model of the system, can be considered as an integrated design and control approach [10], or simply Integrated Design (ID), which aims at simultaneously optimizing the design of a system and its control mechanisms.

Making use of OMSES and MPC, the present work investigates the integration of wind power in the energy system of a remote mine in the Northwest Territories, Canada. The optimal energy supply system was calculated for several scenarios, and the solutions were validated by simulating the optimal systems under actual environmental conditions. This was done using MPC to optimally control the system in a dynamic environment, while considering changes in wind speed and ambient temperature.

## 2. MATERIALS AND METHODS

OMSES was developed to determine the optimal energy supply to meet a mine's energy demands [11]. It is based on the definition of the energy supply system by means of linear equations, expressing energy balances throughout the system, and for each technology installed. These balances represent equality constraints within the system. Constraints are also used to describe capacity limits and include: the maximum power delivered by a piece of equipment (e.g. a diesel generator); the maximum power demand from the grid; or the maximum annual amount of biomass that can be consumed, among others. The decision variables are the installed capacity of each type of technology, as well as the hourly energy and mass balances across the system. The optimal system is that where the corresponding sum of the investment or fixed costs (annuitized), $C_{fix}$, and the operation or variable costs, $C_{var}$, is minimal (Eq. 1). Variable costs include operation and maintenance expenses for the equipment installed, as well as energy costs.

$$C_{tot} = C_{fix} + C_{var} \quad (1)$$

The problem defined here is a mixed integer linear programming (MILP) problem, which is solved using the Branch and Bound method. Figure 1 illustrates the balances in the system for a given set of technologies, where energy and material balances are represented as an interconnected network.

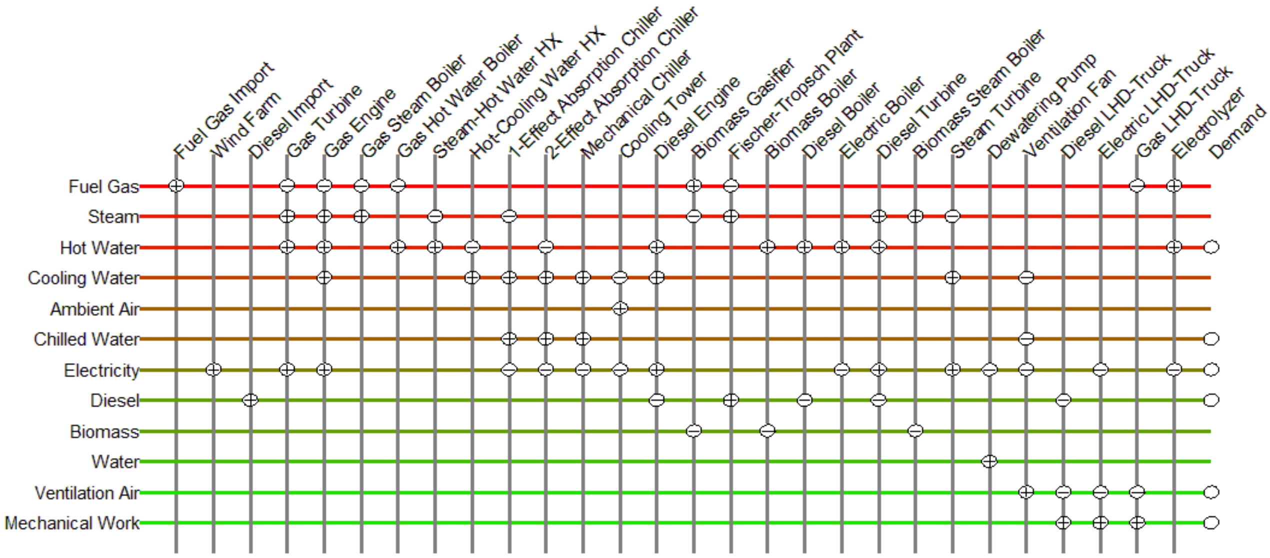


*Fig. 1 – Example of a Superstructure. Vertical lines represent technologies; horizontal lines represent energy and material flow; a positive sign defines production; and a negative sign defines consumption* [11]. *(HX: Heat exchanger; LHD: load-haul-dump vehicle)*

Several variations from previous works are included in the problem with regard to: electricity purchase, additional utility demands and wind power. A grid connection is assumed to be impossible (infinite distance to the connection point). Three additional *utilities* are included: *ventilation, water and mechanical work*. Wind power was included to determine the complexity of integrating such a variable renewable energy source.

In general, the design problem identifies a series of technologies with predefined conversion factors [11]. Because special attention is given to ventilation in the present work, the coefficients that relate the ventilation utility and thermal flows (cooling and heating) are forced to change every hour with ambient temperature. These coefficients are, therefore, functions of the form $\beta(T)=C_p\cdot(T-T_{set})$, where $T$ is the ambient temperature, $T_{set}$ the temperature setpoint and $C_p$ the specific heat, considered constant and in convenient units ($MW/Mm^3/h\text{-}K$, where $Mm^3 = 10^6 m^3$). In this work, the heating required for some consumers is defined as a low grade heat type (e.g. ventilation heating demand, which can be met by low temperature waste heat from a diesel generator, since the temperature to which the ventilation air is heated is normally low). In contrast, a high grade heat demand (*HW*) is also included (e.g. for building heating), whose $T_{set}$ is different and whose load takes the form: $Q(T)=UA\cdot(T-T_{set})$.

Dewatering is treated as a material flow that interacts with energy flow by means of pumps. It is a dispatchable electric load, and therefore can be considered a form of electricity storage. Balance equations (constraints) in water and energy are implemented using the methodology described in [11, 12]. Economic parameters include: the cost of building an underground dam (expressed in economic units per unit of volumetric storage capacity), the investment in pumps and the cost of running them. It was assumed that the dam or water reservoir receives a constant inflow.

From a design perspective, evaluating local renewable resources is complex. The method used here is based on monitored weather data from a location near the mine. The limitation of hourly data – typical of meteorological stations whose data are available online from several institutions, including Environment Canada [13] – is that it is impossible to quantify important factors such as turbulence intensity (*TI*) [14], and therefore the resource evaluation provides optimistic results. The power produced by each installed wind turbine is calculated using wind speed hourly data. Typical 24h wind profiles are calculated for each representative month. Root mean cube (*rmc*) [15] speed is used to calculate the profiles.

In the present work, only the spinning reserve is considered to manage drops in renewable power generation. Mine's electrical load is free from uncertain variability. There are two ways in which the reserve is achieved, even in the absence of renewable energy sources: synchronized generators and electric storage. The drop in power generation from the wind turbine depends on the *TI*. It is a function of the mean wind speed ($v$) in a given interval and its standard deviation in such interval ($\sigma$), i.e. $TI = \sigma/v$. The characterization of *TI* requires a wind speed measurement resolution of at least minutes, preferably seconds, since $v$ is calculated as the 10 minute speed average, and $\sigma$ its characteristic deviation. Given certain values for *TI*, the spinning reserve that compensates for almost any power reduction from the wind farm can be determined, assuming that the drop in wind speed expected is some function of $\sigma$. Throughout this work, $TI = 0.2$ is used with a conservative wind drop of $2\cdot\ \sigma$. Knowing the lowest value of the expected wind provides the value of the maximum expected power drop, which must be countered by a combination of: 1) the remaining capacity of the active generators; 2) the available electricity (power) stored; and 3) the generators in spinning reserve (synchronized with the micro-grid).

$$C^{sr}_{e,ij} = p_{DI}\cdot (\varepsilon\cdot n^{sr}_{PM,ij}\cdot P_{nom,PM} / \eta_{PM}) \tag{2}$$

$$P^{pro}_{PM,ij} \leq n^{op}_{PM,ij} \cdot P_{PM} \tag{3}$$

$$P^{pro}_{PM,ij} \geq (n^{op}_{PM,ij} - 1)\cdot P_{PM} \tag{4}$$

$$n^{op}_{PM,ij}\cdot P_{PM} - P^{pro}_{PM,ij} + n^{sr}_{PM,ij}\cdot P_{nom,PM} \geq n^{op}_{WT,ij}\cdot (P_{WT,ij}|_{HIGH} - P_{WT,ij}|_{LOW}) \tag{5}$$

$$n^{op}_{PM,ij} + n^{sr}_{PM,ij} \leq n_{PM} \tag{6}$$

$$\forall\, i,j \in t$$

Equations 2-6 impose the constraints necessary to update the existing model [11] in order to include the spinning reserve. The number of engines synchronized at every interval is $n^{sr}_{PM,ij}$, while the number of generators supplying power is $n^{op}_{PM,ij}$. Using the methodology described here and presented in [11], the optimal design, as well as an optimal operation plan or schedule for each of the characteristic days (one per month of the year), can be obtained, now including wind power. The results in this paper used the formulation described not only for design optimization, but also in an MPC simulation methodology, making use of the same mathematical model of the mine, in a rolling horizon of 24 hours, with wind forecast of 24 hours in advance. The simulation uses a fixed configuration (design) of the energy system, based on the results of OMSES for the typical demands and environment.

## 3. CASE STUDY

The mine considered in this case study is a remote underground facility with similar location and characteristics as Diavik Diamond Mine in the Northwest Territories, Canada. Therefore, the mine is without a connection to an external power grid and only accessible several months per year by winter road. Demands of electricity, mechanical work, dewatering and some heating and ventilation are calculated based on data accessed online from different sources [16-18].

Diesel consumed by mobile equipment is conveniently transformed into mechanical work. Power demands mainly include consumers such as dewatering, ventilation, compressed air, lights, crushers, mills, backfill plants and general services for workers. All calculations are based on ore production (tonnes). For example, total electricity consumption is calculated at 100 kWh per tonne of ore, while diesel consumption is estimated by 4 liters per tonne ore, for underground and surface operations (1 liters/tonne moved and a strip ratio of 3). The average daily ore production is 5500 tonnes, which yields an average of 22.92 MW of power demand. As ventilation and dewatering were accounted for separately, the figure of 100 kWh per tonne was reduced to 85 kWh/tonne. Constant daily production throughout the year and a normalized daily profile were assumed.

*Table 1. Equipment and matrix of production coefficients* [11]

| Equipment | Nominal Power [MW]* | Capital Cost ($10^3$ CAD) | O&M Cost (CAD/MWh) | Electricity (EE) | Diesel (DI) | Steam (VA) | Hot Water (HW) | Cooling Water (CW) | Chilled Water (RW) | Ambient Air (AA) | Dewatering (DW) | Ventilation (AV) | Mech. Work (MW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Diesel engine | 4.4 | 4400 | 5.0 | **1** | 2.27 | | 0.80 | 0.20 | | | | | |
| HW Boiler | 3.9 | 150 | 1.0 | | | | **1** | | | | | | |
| Electric boiler | 3.5 | 144 | 1.0 | 1.11 | | | **1** | | | | | | |
| Diesel boiler | 3.0 | 130 | 1.0 | | 1.15 | | **1** | | | | | | |
| Mech. Chiller | 2.7 | 185 | 2.0 | 0.21 | | | | 1.21 | **1** | | | | |
| Cooling Tower | 5.0 | 82 | 5.0 | 0.02 | | | | 1 | | **1** | | | |
| VA-HW HX | 5.0 | 50 | 1.0 | | | 1.1 | **1** | | | | | | |
| HW-CW HX | 5.0 | 35 | 1.0 | | | | 1.1 | **1** | | | | | |
| Mobile plant** | 0.2 | 1000 | 150 | | 3.33 | | | | | | | 0.46 | **1** |
| Pump [$m^3$/h] | 30 | 60 | 0.1 | .003 | | | | | | | **1** | | |
| Fan [$Mm^3$/h] | .35 | 30 | 0.1 | 2.5 | | | | $\beta$ | $\beta$ | | | **1** | |

* Nominal installed capacity is in [MW] units except for pumps [$m^3$/h] and fans [$Mm^3$/h]
** Technology included in order to accounting for the interaction of mobile work and thermal loads through ventilation

The dewatering demand is calculated using an infiltration rate that, together with the process water used underground [12], totals 170 $m^3$/h of water to be collected and pumped. The dewatering system is subject to optimization, specifically regarding the number of pumps and water storage capacity. This provides the mine with a dispatchable load, thus the pumps are run when it is more cost effective subject to assuring the safe management of the water underground. The dewatering system is simplified into a set of pumps and one reservoir. Linearity is assumed for the power-capacity relationship and parallel performance. A linear relationship of 3 kW electric per $m^3$/h pumped is considered.

In underground mines, the ventilation system's electric consumption accounts for several megawatts. The power consumption is shared by surface fans and underground fans. It is assumed that the installation consumes 2.5 MW per million cubic meter of air per hour ($Mm^3/h$). It is assumed that the air flowrate is constant whenever ventilation is required underground. The flow-power relationship can be adjusted if the system components are known (fans, louvers, drifts, ducts, etc.) or can at least be estimated from benchmarking.

The mechanical work demand is calculated using estimated diesel consumption. Diesel consumed by vehicles and diverse underground equipment is normally expressed in volume units per tonne of ore moved or hauled. The work output (or power) demanded is calculated by multiplying the fuel consumption and the average thermal efficiency, which is considered 30% in a full duty cycle for the average underground equipment. A two shift operation, with an average of three-hour mechanical work pause between shifts, is assumed. During work breaks, a certain amount of ventilation is needed, especially for blast clearance if blasting operations take place (1.08 $Mm^3/h$ in this work). For the remaining time, ventilation is a function of the applied regulation or dilution criteria (for example, 0.06 $m^3/s$ of air per kW of diesel power equipment in Ontario mines). A diesel demand for surface equipment (mainly hauling trucks) is also considered. The available technologies for the mine operation, their costs and coefficient matrix [11], are shown in Table 1.

*Table 2. Problem Inputs*

| | | | |
|---|---|---|---|
| Mine | Diavik Diamond Mine | | |
| Company | Rio Tinto | | |
| Type | Underground | | |
| Product | Diamonds | | |
| Production | Year | 2.0e6 | tonne ore |
| | Day | 5.5e3 | tonne ore |
| Electricity* | Energy Intensity** | 85 | kWh/tonne |
| | Mean power (all consumers) | 23 | MW |
| Mobile | Diesel intensity UG | 4 | liter/tonne ore |
| | Diesel intensity Surface | 4 | liter/tonne ore |
| | Average efficiency | 30% | |
| | diesel energy density | 10 | kWh/liter |
| | Operation time | 18 | hours/day |
| | Mean power | 3.65 | MW |
| | Engine shaft work intensity | 12 | kWh/tonne ore |
| Ventilation and Diesel | Regulated requirement | 0.06 | $m^3/s/\ kW$ |
| | Operational safety factor | 2 | |
| | Total | 0.12 | $m^3/s\ /kW$ |
| | | 0.432 | $Mm^3/h\ /MW$ |
| Ventilation Electricity | Surface | 0.5 | $MW/\ (Mm^3/h)$ |
| | UG | 2 | $MW/\ (Mm^3/h)$ |
| | Total | 2.5 | $MW/\ (Mm^3/h)$ |
| Wind | Mean speed | 6.68 | m/s |
| | $V_{rmc}$ | 7.9 | m/s |
| | $P_{rmc}$ | 1479 | kW |
| | $WPADF_{rmc}$ (2012)*** | 1.056 | |
| Temperature | Annual mean | -4.57 | °C |
| | January mean | -26.8 | °C |
| | July mean | 16.8 | °C |
| | $T_{set}$ comfort level (Ventilation/Building) | 15/20 | °C |
| | *UA* (buildings) | 0.1 | MW/°C |
| Dewatering | Hourly average | 170 | $m^3/h$ |

*At Diavik there is an ore processing plant and a backfill plant
**Not including utility consumers: ventilation, dewatering, cooling or heating
*** Wind power air density factor (WPADF), due to temperature variation

Local weather and wind speed was obtained from Inner Whalebacks weather station [13] and validated with data from several mine reports [16, 18]. Normalized wind profiles for characteristic days were calculated and used in the design problem, together with the corresponding monthly *rmc* wind speed values. For the design problem, typical 24h temperature profiles were calculated using the *Erbs coefficients* [19] and monthly average temperatures. For the simulation problem, actual hourly data was used [13].

Diavik Diamond Mine installed wind power to reduce its diesel imports [16, 17]. The mine declares, for its four turbine wind farm, a 10% average penetration factor (52% maximum), offsetting approximately 10% of the diesel demand for power generation [18]. For the mine, the wind farm project has a payback period of 8 years. Neither the discount rate, nor the operating costs of the wind farm are declared (although total cost of the wind farm reported by the company is CAD 31 million [21]). Each E-70 Enercon wind turbine has a nominal output of 2.3 MW (air density standard conditions), and a 71m rotor diameter, with the hub located at 63m (Enercon). A conservative reduction of 10% in the nominal output was applied to account for auxiliary equipment for special Arctic conditions.

Wind farm losses were taken as 20% of the gross generation [20]. Using $\rho_{air}$ =1.225 kg/m$^3$ and removing 15% of installation costs, the wind turbine unit cost is calculated as 3300 CAD/kW. Heat storage are considered CAD 18500/MWh. The cost for water storage is CAD 100 per cubic meter [12]. Installation, procurement, engineering, and other costs are added as 25% of equipment costs (Table 1). The energy system's capital cost is annuitized using a capital recovery factor, with a 10 year life of equipment and operations and a 10% discount rate. Diesel is acquired in the market (delivered at the mine) at an equivalent cost of CAD130 per MWh. Detailed parameterization of the mine's energy system is shown in Table 2.

Several scenarios are explored in the following section. In order to reduce the scope of the present work, electrical storage was not allowed to take part in the solutions. The scenarios are:

- Scenario I: No heat recovery, no wind turbines
- Scenario II: *BAU:* Heat recovery, no wind turbines. Conservative design imposed for diesel generators (10 units) and boilers (9 units) for this and the following scenarios
- Scenario III: Wind turbines allowed, no spinning reserve logic
- Scenario IV: Wind turbines from solution of scenario III, spinning reserve logic included
- Scenario V: Wind turbines allowed, spinning reserve logic included
- Scenario VI: Four wind turbines imposed, spinning reserve logic included

## 4. RESULTS

Inner Whaleback's weather station, located on a small island at Great Slave Lake [13], measures the wind speed at enough height and free of obstacles that it is considered a good approximation of the conditions at the Diavik mine. Both Weibull and Rayleigh frequency distribution functions (*h*), were calculated using the Generalized Reduced Gradient (GRG2) nonlinear optimization code from Microsoft Office Excel Solver tools, which fitted c and k parameters based on the least square method. Subsequently, the Weibull distribution (shape parameter=2.364, scale parameter= 7.425) was used to calculate the power produced at each speed by the wind turbine.

Table 3 shows an estimation of the power that can be produced on site using the selected wind turbine. For example, using the number of wind turbines installed at Diavik (four), an equivalent wind farm with the weather conditions of Inner Whaleback would yield (including all losses) 15.85 GWh annually. When the air density is corrected (using the $WPADF_{rmc}$), the value reaches 16.74 GWh. These values correspond to a 27.3% capacity factor over 8760 hours of operation.

*Table 3. Wind speed data and wind turbine output (Inner Whaleback year 2012)*

| Magnitude | Value | Units |
|---|---|---|
| Mean speed | 6.68 | m/s |
| $Power\|_{mean}$ | 0.40 | kW |
| Root mean cube (*rmc*) speed | 7.90 | m/s |
| $Power\|_{rmc}$ | 0.60 | kW |
| Expected annual production E-70 ($\rho_{air}$ =1.225 kg/m$^3$) | 5.50 | GWh |

Assuming that all the energy produced can be integrated in the local grid (without energy storage), the aerodynamic, electrical and mechanical losses will reduce the energy harvested and the capacity factor. Considering that 80% of the wind power system can be used, including the energy required to heat the blades (in case of ice formation) and the electronic components, the wind farm would yield 16.02 GWh with a capacity factor of 21%. Rio Tinto reports a characteristic wind speed of 7.22 m/s at a height of 60m, with an expected annual yield for the wind farm between 15 and 17 GWh (21-26% capacity factor) depending on the losses considered. The company also reports an average wind speed of 6.3 m/s, a value close to the 6.68m/s Inner Whaleback.

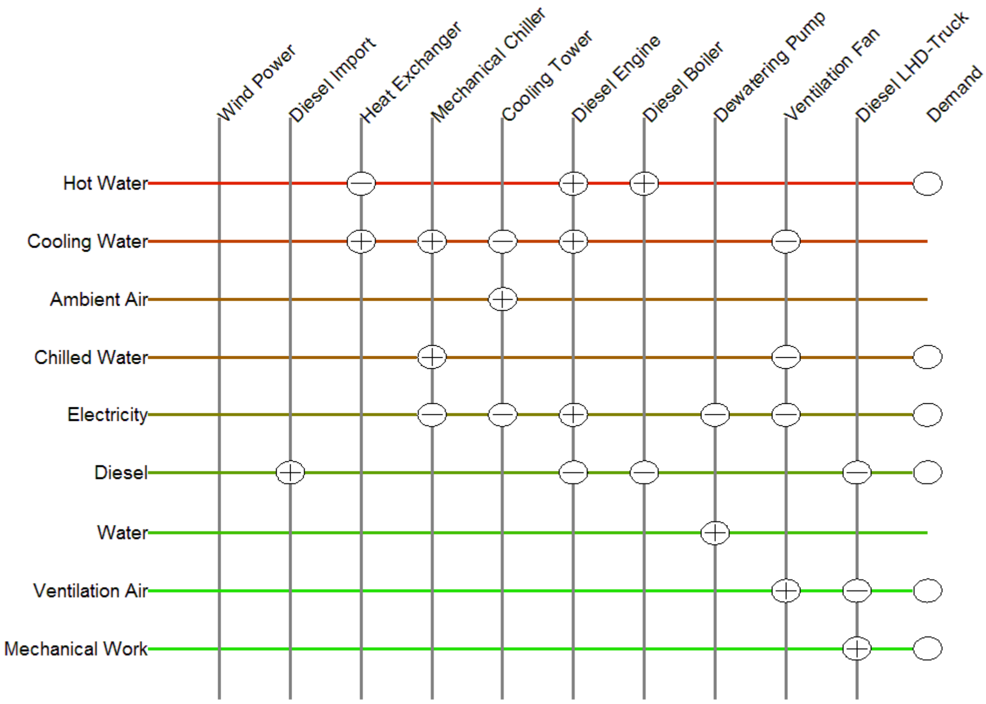


*Fig. 2. OMSES Result Superstructure with the installed technologies*

Figure 2 shows the graphical result of the technologies included in the superstructure solution of the design problem, for all scenarios considered. Heat storage, although part of the optimal solution of several scenarios (II to VI), was not represented to reduce the complexity of the representation. Table 4 summarizes the results of six scenarios, and compares each with scenario II (*BAU*). Although the solutions of scenarios III to VI differ significantly in variable cost savings (diesel cost primarily), their total annual cost vary marginally when they are compared to scenario II. Therefore, no definitive conclusion can be drawn from the results regarding which may be the optimal solution in practice (real system, not the model).

Additional parameters to evaluate the risk of each option (2, 4 or 8 wind turbines) should be considered. For example, scenarios V and VI have similar total annual cost savings (0.07% and 0.02%). Thus, scenario V can be considered a more attractive investment because its lower investment results in a lower financial risk. However, should the diesel consumption be dramatically reduced, scenario VI or even IV can be considered better options. Wind turbine capacity factors (CF) (Table 4) are in agreement with those reported for the actual wind farm [18].

Table 5 illustrates the difference in variable cost savings between scenarios IV-VI and scenario II (or *BAU*), for both design and simulation problems. The MPC simulation includes the spinning reserve (Eq. 2-6) and air density correction and, apart from the dewatering pumps which are effectively dispatchable loads, does not include electrical storage. In both the design optimization and the MPC simulation formulation, spinning reserve ($n^{sr}_{PM,ij}$) can be decreased by shifting load demand (dewatering). This reduces the load ($P^{pro}_{PM,ij}$) of the diesel generators active and producing ($n^{op}_{PM,ij}$), which then reduces the need for engines in spinning reserve (Eq. 5). As stated previously, the use of spinning reserve for the calculations in the design stage significantly overestimates the diesel consumed for the reserve engines. It should be remembered that the design problem uses *rmc* speed values to calculate wind power, and although these are valid to calculate monthly and annual wind energy harvested, they poorly represent what happens on individual days.

*Table 4. Scenario results from the design optimization problem (mine life 10 years)*

| | | Scenario | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|---|---|
| Diesel engine | - | | 6 | 10 | 10 | 10 | 10 | 10 |
| Electric boiler | - | | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Diesel boiler | - | 9 | 9 | 9 | 9 | 9 | 9 |
| Single Effect Abs Chiller | - | 0 | 0 | 0 | 0 | 0 | 0 |
| Mechanical Chiller | - | 2 | 2 | 2 | 2 | 2 | 2 |
| Cooling Tower | - | 1 | 2 | 2 | 2 | 2 | 2 |
| VA-HW HX | - | 0 | 0 | 0 | 0 | 0 | 0 |
| HW-WR HX | - | 4 | 4 | 4 | 4 | 4 | 4 |
| PUMP | - | 6 | 6 | 6 | 6 | 9 | 15 |
| FAN | - | 5 | 5 | 5 | 5 | 5 | 5 |
| Diesel mobile plants | - | 19 | 19 | 19 | 19 | 19 | 19 |
| Electric mobile plants | - | 0 | 0 | 0 | 0 | 0 | 0 |
| Wind turbines | - | 0 | 0 | 8 | 8 | 2 | 4 |
| Electric storage | MWh | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Heat storage | MWh | 0.0 | 8.1 | 12.8 | 12.8 | 10.1 | 9.0 |
| Water storage | m3 | 0.0 | 0.0 | 0.0 | 0.0 | 1000.0 | 984.2 |
| Investment in equipment | MCAD | 55 | 76 | 138 | 138 | 91 | 107 |
| Total annual cost | MCAD/year | 112 | 102 | 102 | 103 | 102 | 102 |
| Annuitized fixed cost | MCAD/year | 9 | 12 | 22 | 22 | 15 | 17 |
| Variable cost | MCAD/year | 103 | 90 | 80 | 81 | 87 | 85 |
| BAU variation | Investment | -27.15% | | 82.23% | 82.23% | 21.00% | 42.05% |
| | Total annual | 9.63% | | -0.37% | 0.67% | -0.07% | -0.02% |
| | Variable | 14.65% | | -11.63% | -10.45% | -2.94% | -5.76% |
| Imported Diesel | GWh | 756.86 | 655.93 | 576.62 | 577.08 | 635.74 | 615.99 |
| | | 15.4% | | -12.1% | -12.0% | -3.1% | -6.1% |
| Wind performance | Penetration | 0 | | 17.10% | 16.99% | 4.20% | 8.45% |
| | CF | 0 | | 24.21% | 24.06% | 23.80% | 23.93% |

*Table 5. Difference between design and simulation variable costs savings (relative to Scenario II)*

| | Scenario V (2 WT) | Scenario VI (4 WT) | Scenario IV (8 WT) |
|---|---|---|---|
| Design (Table 4) | 2.93% | 5.76% | 10.45% |
| MPC Simulation | 2.76% | 5.65% | 11.26% |

Assuming spinning reserve was not necessary, and with only dispatchable pumps as an electric storage, a sensitivity analysis of OMSES optimal design was carried out regarding the life of the project. This affects the capital recovery factor. Figure 3 shows increased turbine installation with longer mine's life, and greater savings relative to BAU. But curves shown in Fig. 3 should be regarded as upper bounds of the more complex problem that requires spinning reserve and allows electric storage in the form of electric batteries. Diminishing returns appeared when flexing the number of wind turbines installed.

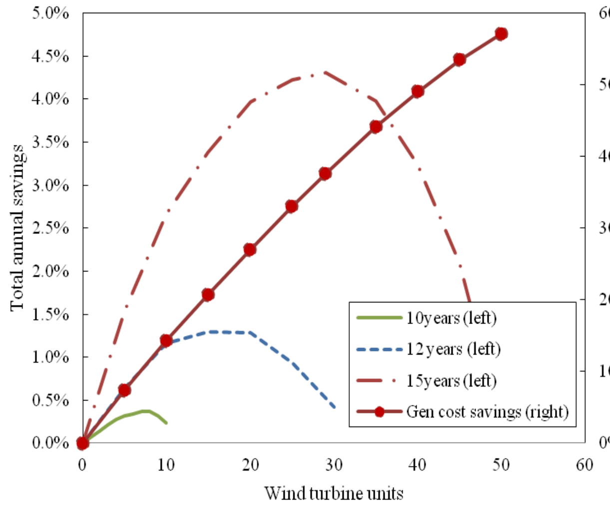


*Fig. 3. Project life influence on optimal wind turbine units and variable costs*

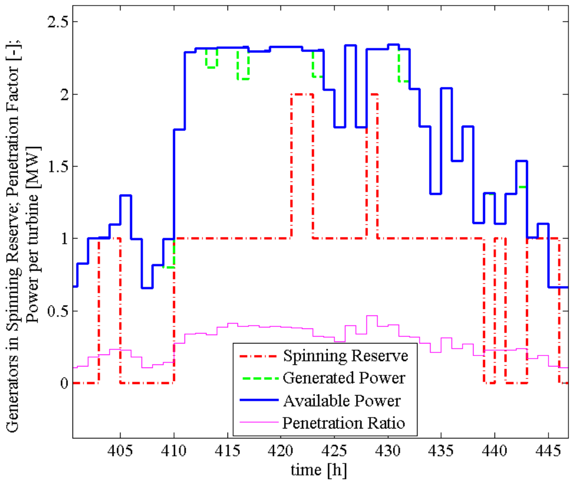


*Fig. 4. Spinning Reserve and Wind Power Curtailment during January for Scenario VI*

Figure 4 illustrates the performance of the wind farm and the total spinning reserve needed, i.e. the number of engines synchronized ($n^{SR}_{PM,ij}$). The data represents several hours of January from the MOC simulation, after OMSES optimal design calculation, and reflects the power per wind turbine (in *MW*). The *power generated* by the wind farm (dashed line) is always equal or lower than the total *available power* (solid line). The penetration ratio *(PR)* is calculated as the power generated by the wind farm (losses included) divided by the total power consumed in the mine. The curtailment (difference between available WT power and actual delivered) appears for significantly different penetration ratios, i.e. at t=410 (*PR*=14.0%) or at t=417 (*PR*=40.0%). The methodology is sensitive to the cost of operating an additional engine for spinning reserve. The maximum *PR* in January (scenario VI with air density correction) was 46.7% (t=428), needing two generators in spinning reserve.

It should be noted that during the simulation, OMSES optimal design was found unfeasible, due to shortages of cooling capacity, derived from the use of typical days with average temperatures during the month of July. Thus, although the optimal design could be solved as well during the MPC simulation, it is recommended the use of safety factors when optimizing the design using OMSES for those technologies in which the greatest demand is significantly different from the typical demand.

## 6. CONCLUSIONS

The present work investigated two aspects related to optimal energy supply systems: the consideration of wind power, using *rmc* wind speed to characterize the resource within the problem of optimal design; and the robustness of the optimal design previously determined under a more realistic operating environment, i.e. through simulation.

The case of a remote underground mine was considered. Its demands were calculated based on data from an existing operation – Diavik Diamond Mine. Diavik is an actual hybrid microgrid. The concepts that apply to Distributed Energy Resources and Integrated Design were applied to the mine's energy system. The usefulness of the wind data obtained from a nearby location was assessed by comparison with the reported energy production declared by the operators of the existing wind farm at Diavik.

Six scenarios with different constraints were considered in the design stage. In all scenarios, the wind farm was found to be cost-effective, although the optimal number of wind turbines differed. For instance, when the formulation included constraints regarding spinning reserve, the optimal design included two wind turbines. Conversely, for the spinning reserve unconstrained design problem, the optimal solution included eight turbines. For the real mine, Rio Tinto reports a payback period of less than eight years for Diavik's wind farm, demonstrating the cost-effectiveness of such an investment, which is in agreement with the results obtained.

Further investigations focusing on the optimal design were addressed regarding the life of the mine. The main conclusion after running a series of parametrical analyses was that the size of the wind farm experiments eventually diminishing returns, even if the technology is cost-effective under the economic environment defining a particular problem.

The limitation of the design problem to generate practical solutions was subsequently investigated. The design was improved manually in order for it to meet the mine's demands throughout the whole simulation interval (one year). However, this approach can be substituted by a relaxation of the constraints of the simulation problem. This means allowing the MPC-based algorithm to use additional units of technology, thus increasing the capacity resulting from the optimal design problem. These additional units entail a cost, but feasibility can thus be ensured. This cost can be related to the installation cost of the specific piece of technology. Future studies should investigate the effectiveness of this strategy. The corrected design was simulated under actual environmental conditions of temperature and wind speed. The results from the simulation stage validated the design approach regarding the use of *rmc* wind speed to characterize this renewable energy resource, as well as the methodology to ensure proper spinning reserve to deal with wind variability. An MPC approach for simulation and operation optimization was confirmed as necessary to evaluate not only OMSES optimality, but also feasibility. OMSES, however, showed that it was robust and reliable enough to assess the cost-effectiveness of renewable, naturally variable energy resources in mine energy systems in remote locations.

One of the limitations of OMSES is the use of a stationary situation of the mine, i.e. it assumes that the production rate, depth and grade of the mine are the same for the whole operating life. This limitation will be investigated in future work, as well as the effect of electricity storage.

## 7. ACKNOWLEDGEMENTS

This work was developed within the framework of research projects of the Smart Underground Monitoring and Integrated Technologies for Deep Mining (SUMIT) program, funded by Ontario Research Fund for Research Excellence, Round 5. The authors are also indebted to Ms Maxine Myre who reviewed the manuscript and made valuable suggestions to improve it.

## 8. NOMENCLATURE

- $C$ Cost
- $C_p$ Specific heat [MW/Mm3/h-C]
- *CAD* Canadian dollars
- $n$ number (units, i.e. diesel generators)
- *PR* Penetration Ratio
- $p$ price
- $P$ Power [MW]
- $Q$ Heat [MW]
- *SR* Spinning Reserve
- $t$ time set (hours and days)
- $T$ Temperature [C]
- *TI* Turbulence Intensity [-]
- *UA* Product of transmittance and area [MW/C]
- $v$ speed [m/s]

***Superscripts***

- *op* in operation
- *pro* produced
- *sr* spinning reserve

***Subscripts***

- build building
- e energy
- *fix* fixed
- i day
- j hour
- *nom* nominal
- *PM* prime mover (i.e. diesel generator)
- *rmc* root mean cube
- *set* set point
- *tot* total
- *var* variable
- *WT* wind turbine

***Greek letters***

- $\eta$ efficiency [-]
- $\sigma$ standard deviation
- $\varepsilon$ idling fuel consumption factor
- $\beta$ heating/cooling coefficient
- $\rho$ density [kg/m$^3$]

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