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Optimal synthesis of energy supply systems for remote open pit mines

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HIGHLIGHTS

- Optimal mine site energy supply methodology is established.
- Methodology permits innovative, lower cost, energy supply solutions to be identified.
- The methodology allows for electricity and syngas storage and diesel and biomass bunkering.
- A remote, open pit mining operation located in Northern Ontario is considered as a case study.
- The optimal solution includes some of the more exotic options for mine site energy supply.

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ABSTRACT

The primary motivation underlying the proposal of polygeneration systems for mine sites is to increase the efficient use of natural resources by combining different technologies and energy resources while satisfying energy service demands. For many mineral producers, particularly in Canada's mining extremes of climate and depth, energy in support of mineral production can be the second largest cost center after labor. A generic methodology is proposed for the design of energy supply systems in mine sites, based on a search for the minimum discounted cost of energy supplied for all feasible different plant configurations. These configurations can be represented within a connectivity matrix which corresponds to a network representation. A Mixed Integer Programming formulation is set out for the multiperiod synthesis and operational planning problem. This is characterized by i) binary variables for the selection of technologies, ii) integer variables for the determination of the number of units installed, and iii) by continuous variables for the representation of energy and economic flows. Through the integration of particular energy supply strategies matching specific mine circumstances (on-grid, remote, degree days, etc) and consideration of technologies that improve energy efficiency, hitherto not considered new technologies and demand management systems or new perspectives on optimal mine site energy supply can be investigated. Some of these investigations identify the economic conditions through which biomass energy feedstocks should be used, for direct heat production, for gasification and providing for Fischer–Tropsch syndiesel manufacture. As well as integrating demand from mobile diesel-fueled plant into an optimization procedure this analysis shows how the techniques can be used to explore economic conditions of threshold prices for biomass (purpose-grown biomass and peat are considered herein) and trucked-in diesel. The methodology also allows for electricity and syngas storage and diesel and biomass bunkering. Within the paper the energy demands for a remote, open pit mining operation located in Northern Ontario are considered as a case study to illustrate the technique and investigations. As expected, for mines close to electricity, natural gas, and diesel distribution infrastructures, the optimal choice is to connect. When a constraint is applied specifying that connection is not possible, as would be for the case exemplified, the optimal choice includes some of the more exotic options for mine site energy supply.

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1. Introduction

Canada is the global leader in production of potash and uranium and a major producer of coal, nickel, cobalt, titanium, diamonds, zinc, molybdenum and salt. Canada's mineral-processing industry is significant, with more than 40 nonferrous metal smelters and refineries [1]. The industry contributed $36 billion to Canada's gross domestic product in 2010; this included $8 billion in mineral extraction and $28 billion in mineral processing and manufacturing [2]. Canadian mining and metals companies invested $548 million in research and development in 2010 and the industry plans to invest $136 billion in projects over the next decade, with priority areas for innovation including tailings management, energy efficiency and effective exploration [2].

Energy consumption within the mining industry and energy prices are rising and thus there increased need to reduce consumption, and improve primary energy utilization to maintain competitiveness within the mining sector by reducing input costs [3]. Given the significance of energy costs in operating expenses, efficiency of energy production and use must be improved in the energy-intensive mining sector [4]. Improvement in the use of primary energy can be achieved by a combination of energy efficiency and process integration. As a consequence of the better use of energy resources, production costs decrease, and since less energy is used/wasted, less greenhouse gases are emitted. Having a comprehensive energy strategy is key to cost effective mining operations.

Process integration and polygeneration are promising tools which reach the double objective of increasing the efficiency of utilization of natural resources, and also of reducing the environmental impact [5], without decreasing the quality of the services provided.

Polygeneration is referred to as an extension of the principles of Combined Heat & Power (CHP, or cogeneration) and Combined Heat, Power & Cooling (CHPC, or trigeneration), integrated in the generation of a minimum of 3 products (Fig. 1). Polygeneration is herein considered as equivalent to Distributed Energy Resource (DER), from which some concepts and methodologies are taken in combination with ones from Distributed Generation (DG) (precursor of DER, focused on electricity generation).

Polygeneration technologies, underexploited in the mining sector, are not a new concept and have been applied to other industry sectors with success [6–10], providing maximum energy usage as a consequence of increasing energy efficiency, and reducing environmental burden and the unit cost of final products. For the minerals extraction sector, rather than considering these aims separately, design under sustainable criteria, accounting for them simultaneously, may lead to substantial enhanced economic and environmental benefit and competitiveness.

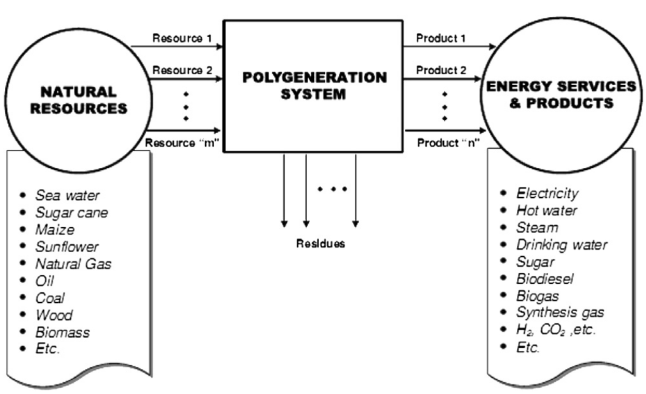

Fig. 1. Polygeneration: a multi-resource, multi-product transformation process [5].

Process integration is a family of methodologies for combining several processes to reduce consumption of resources [11]. It started as mainly heat integration stimulated by the energy crisis in the 1970's. According to Serra et al. [5], process integration is based on thermodynamic and economic analysis not only of individual components but also of the entire system. Fundamentals can be found in exergy analysis [12], pinch analysis [13] and mathematical optimization techniques applied to process synthesis [14,15].

Heat has not been considered in an integrated manner in the mining sector, which makes the combination of process integration and polygeneration of great interest to sector operators, being a superior option to conventional stand-alone plants. However, due to the wide availability of different energy sources and equipment technologies, the synthesis and design of energy systems is not straightforward and must accommodate these complexities [3].

Lopes et al. [16] and Chicco and Mancarella [17] have generalized Distributed Generation (DG) focused on power generation, to the wider concept of multi-generation or Distributed Energy Resources (DER), where energy transformations (*e.g.*, fuel to electricity) take place in a decentralized way, in contrast to, for example, the conventional power and heat generation (centralized and independent). Mendes et al. [18] review the most significant approaches in the area of Microgrids (MG) when optimization problems need to be solved. Simulated Annealing (SA), Genetic Algorithms (GA), Ant Colony (ACO) and Particle Swarm Optimization (PSO) are representative of Metaheuristic methods, while linear programming (LP), Integer programming (IP) and Mixed Integer Linear Programming (MILP) solve optimization problems through classical methods [18].

According to Ref. [19], MILP methods are adequate to study polygeneration energy systems from the points of view of synthesis, design, and optimization. A "superstructure" is created, i.e., a matrix that embeds all options of energy conversion (equipment) with these options being represented by binary variables (0/1 = not-installed/installed). Energy and monetary flows are represented by continuous variables, and with the help of equality (or inequality) constraints, the pertaining logical and/or physical relationships are introduced into the model.

An approach for the optimal synthesis of polygeneration energy supply systems for remote open-pit mine sites is presented herein, which represents one of the extensions mentioned in the cornerstone work published in Carvalho & Millar [3]. The same demand data and a common core formulation are utilized, to make the following contributions: i) Electricity grid connection is a free decision variable (rather than expressed as a formulation constraint); ii) Partial electricity grid connection (in the case of finite import/export capacity limits governed by cable rating); iii) Avoidance of capacity charges at times of peak demand for electrical power (when peaks are characterized by a probability distribution function); iv) Assimilation of complex electricity tariff arrangements (such as those in Ontario) into the formulation); v) Details on the extension of a mathematical formulation of the optimization problem that considered electricity and heat storage, such as in Ref. [20], to allow for syngas storage and biomass and diesel bunkering.

Developments i), ii) and v) arose in facing the complexity of the mining operations, many times located in remote areas, and account for some of the particularities of studying an open-pit mine in the province of Ontario. Within the formulation presented, methodological extensions i) and ii) permit the assessment of the optimum economic distance at which connection to an electricity transmission and distribution grid would be declined by a microgrid. This is not something that was addressed in the recent work by Zhou et al. [21]. The methodological extensions for storage of the