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Optimal design of hybrid energy systems incorporating stochastic renewable resources fluctuations

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ABSTRACT

The potential impacts of variability and intermittency in renewable resources on the design of stand-alone renewables-based energy systems incorporating storage are addressed at the design stage. The framework developed accounts for climate-based variability by considering different stochastically generated renewable input scenarios in the evaluation of system reliability. Operational constraints which control the availability and discharge of storage technologies based on previous storage states and technology start-up times are incorporated into the energy system model to account for the intermittent power output from renewables. A cost-reliability bi-criteria sizing problem is solved for two cases of a remote Canadian mine to demonstrate that intermittency in generation can influence technology choices, system configuration and system operation. Approximations to the non-dominated fronts are generated with NSGA-II, and the operating characteristics of the maximum-reliability designs generated in the cases are investigated. The methodology provides the decision maker with information about a number of operable designs and an understanding of the performance risks associated with the selection of any given design.

1. Introduction

Industrialization and rapid population growth have led to a steady rise in the demand for energy. The global energy demand is expected to rise by between 30% and 40% by 2040 [31,51]. The industrial sector is the chief consumer of energy, demanding 42.5% of the world's electricity generation in 2014, along with significant quantities of coal, natural gas and oil [30]. The mining industry accounts for a significant portion of this energy demand. Mining operations involve several energy intensive processes such as drilling, excavation and blasting [53], and energy costs have been shown to represent between 15 and 21% of the total cost of production in the mining industry [45,67]. The rising demand for metals around the world, coupled with the depletion of readily accessible ore deposits, has led to mining operations moving to more remote locations where they often face significant energy problems since grid electricity is usually unavailable. Such mines typically resort to the use of diesel generators, leading to a substantial increase in the overall mining cost. The fuel is transported over large distances using trucks, raising safety concerns, and the of diesel generators also leads to significant greenhouse emissions, translating to high carbon footprints. These challenges, along with increased pressure from governments, have driven mining operations to seek alternative sources of energy.

Energy generation from renewables is considered to be the most promising solution to the mining industry's energy challenge [53]. Remotely located mines usually have good access to land and are often located in regions with extreme climatic conditions; making them ideal for renewable energy use. Operating mines entirely on renewable energy offers several advantages which are attractive to mine owners, some of which include: energy security over mine lifetime, reduction in operating (fuel, emissions and transportation) costs, lower environmental impact, and improvement of overall plant safety because of reduced need for transportation and storage of flammable compounds. Despite these advantages, the use of renewables-based energy systems as the primary energy sources in continuous processes has been limited due to the variable and intermittent nature of renewable resources. Energy storage integration is therefore critical if renewable generation is to achieve higher levels of penetration into the mining industry. Energy storage helps to address the

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α	scale parameter for Weibull distribution [m/s]
$\overline{X}$	set of non-dominated designs
$\overline{x}_n$	nth non-dominated design
β	shape parameter for Weibull distribution
$\eta_{bat,ch}$	battery charging efficiency, unitless
$\eta_{bat,dis}$	battery discharge efficiency, unitless
$\eta_{inv,ac-dc}$	AC-DC inverter efficiency, unitless
$\eta_{inv,dc-ac}$	DC-AC inverter efficiency, unitless
$\overline{LPSP}_m$	modified loss of power probability, unitless
$\overline{OP}$	discharge operating scheme number
$\dot{D}el(t)$	instantaneous electrical demand of the mine [MW]
$\dot{D}th(t)$	instantaneous thermal demand of the mine[MW]
$\dot{E}load(t)$	total electrical load, made up of mine demand and parasitic requirements [MW]
$\dot{E}RES(t)$	renewable energy system gross electrical output [MW]
$\dot{E}_{dumped}(t)$	rejected electrical energy [MW]
$\dot{E}_j\,in(t)$	energy input into storage option j [MW]
$\dot{E}_{PV}\,gen(t)$	electrical energy output from PV [MW]
$\dot{E}_{wind}\,gen(t)$	electrical energy output from wind generator [MW]
$\dot{G}DNI(t)$	instantaneous direct normal irradiance $[W/m^2]$
$\dot{G}tot(t)$	instantaneous global horizontal irradiance $[W/m^2]$
$\dot{Q}_{AA-CAES}\,heating(t)$	heat to plant from AA-CAES system [MW]
$\dot{Q}_{MTS}\,heating(t)$	combined heat to plant from power tower and MTS systems [MW]
$\dot{Q}RES(t)$	renewable energy system gross thermal output [MW]
$\dot{S}_\tau\,el$	unmet electrical load [MW]
$\dot{S}_\tau\,th$	unmet thermal load [MW]
ψ_τ	binary variable representing state of storage options in time period τ, unitless
$\upsilon(t)$	instantaneous windspeed [m/s]
A_i^{gen}	area of generation unit i $[m^2]$
C_j^{out}	nominal output capacity of unit j [MW]
C_j^s	installed storage capacity of unit j [MWh]
C_i^{gen}	nominal capacity of generation option i [MW]
$CC(\overline{x})$	capital cost of design $\overline{x}$ [€]
dt_f	elapsed time since last system failure [min]
E_τ^{ext}	external energy requirement in time interval τ [MWh]
H	wind turbine hub height [m]
i	generation option
j	storage option
n_g	number of renewable generation options
n_s	number of energy storage options
N_{bat}	number of battery units
N_{st}	battery storage capacity [h]
N_T	number of wind turbines
N_{year}	number of renewable input scenarios
P_R	rated power of wind turbines [W]
$S_j(t)$	accumulated energy in storage option j at time t [MWh]
$t_{start-up}$	startup time of storage technologies [min]
U_j^s	energy-specific cost of storage option j [€/kWh]
U_i^{gen}	unit cost of generation option i [€/m^2]
U_i^{out}	capacity-specific cost of storage option j [€/kW$_e$]
EE	total external energy requirement [MWh]
κ	rate of battery self-discharge [%/day]

variability and generation-demand imbalance challenges associated with renewables generation [8]. Storage options integrated with renewables need to be able to serve three main purposes in order provide smooth, uninterrupted power and maximize system efficiency and reliability: load shifting, standby reserve and power quality management [22]. The design of a standalone renewable energy system will involve the selection and sizing both renewable generation and energy storage technologies.

The challenge of accounting for renewables climate-based variability in energy systems design and sizing has been addressed by several researchers. Two major approaches have been used to account for the stochastic nature of renewables: probabilistic and time-series approaches. In the probabilistic approach, all the variables participating in the energy conversion process are modelled as random variables [62]. The performance of the energy system is assessed analytically by combining the probability distribution functions (PDFs) of the variables [13]. Karaki et al. [34], Tina et al. [63], Khatod et al. [37] and Gooding et al. [26] applied the approach to PV-wind and PV-wind-diesel systems, with the approach recently extended by Paliwal et al. [52] to PV-wind-battery systems. With the time-series (chronological) approach, the amount of renewable resource available at a given time is modelled as a single value which is considered typical for that time instant. The resource availability over the entire period is therefore represented by time series data. With this approach, climate-based variability is incorporated by considering multiple time-series data when evaluating the performance of any energy system. The chronological approach was demonstrated by Kaplani and Kaplanis [33] for PV-battery systems. More recently, Amusat et al. [4] applied this approach to systems integrating multiple thermal and electrical generation and storage technologies.

The intermittent nature of the wind resource has been accounted for in planning and sizing of energy systems integrating wind and diesel generation [11,12,37]. The works constrain the maximum fraction of the load which can be met directly from wind generation, forcing a significant portion of the base load to be met from dispatchable energy sources (diesel generators). Weisser and Garcia [68] recommend limiting the contribution of wind generation to the energy mix to about 30% to ensure energy system stability. Several works have also considered how energy storage could be used to increase the wind contribution to the energy mix [65,15]. The incorporation of wind penetration limits is particularly applicable for wind integration into the energy grid where other non-renewable sources are readily available.

However, very little has been done to address the intermittency challenge in the sizing of standalone systems wholly dependent on renewables generation. For such systems, power fluctuations are a serious issue since diesel generation is unavailable. The lack of attention to this area has primarily been because most works on standalone energy systems design consider only battery storage [47,1,60,64]: the instantaneous response times of batteries mean that the power fluctuations do not need to be considered separately during sizing. However, works in literature [29,40]