Renewable and Sustainable Energy Reviews 93 (2018) 451–472

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Towards the stand-alone operation of data centers with free cooling and optimally sized hybrid renewable power generation and energy storage

Ali Habibi Khalaj[a,*], Khalid Abdulla[a], Saman K. Halgamuge[b]

[a] Department of Mechanical Engineering, The University of Melbourne, Parkville, Victoria, Australia
[b] Research School of Engineering, The Australian National University, Canberra, Australia

ARTICLE INFO

Keywords:
Data center
Cooling system
Wind power
Solar energy
Renewable power plant
Battery energy storage
Optimal sizing

ABSTRACT

Recent increases in the global demand for IT services have increased the power consumption, total ownership costs and environmental footprint of data centers. Recent efforts to reduce these effects have focused on either their cooling systems, or their power systems. In this paper, we have developed an integrated approach to minimize the total power demand of data centers, whilst their reliance on power imported from the grid is minimized. First, the power demand of data center has been reduced utilizing various air-side economizer-based cooling systems. Since the effectiveness of economizers significantly depends on the local weather conditions, 42 stations in major cities across the world have been considered. A more than 80% reduction in total cooling power consumption is achieved by using the most appropriate air-side economizer at each location. Second, the reliance of data centers on power imported from the grid is minimized utilizing on-site hybrid renewable power generation and energy storage. The on-site renewable power generation and capacity factors have been calculated for 1 MW wind and solar renewable power plants to identify the location with the highest renewable power generation capability. The optimal size of a hybrid renewable power plant, and associated battery energy storage system, is also determined for each data center using linear programming to minimize total levelized costs. Finally, the optimal location for constructing and operating the most energy efficient, cost-effective and sustainable data center has been identified by calculating its level of independence from the power grid. It is found that the level of grid independence increases as we move away from the equator, for example more than 50% grid independence can be achieved at Regina station located in Canada.

1. Introduction

The worldwide demand for data centers (DCs) has recently skyrocketed. This has significantly increased their power consumption and total ownership cost. The increase in their power consumption also contributes to CO_2 emissions and global warming, as carbon-intensive fuels such as coal and natural gas are the main source of power generation across the world. These issues have motivated research within academia and the Information and Communications Technology (ICT) industry to increase the efficiency and minimize the environmental footprint of DCs.

A majority of recent research investigating these goals have focused on improving the performance of DCs in three main "areas": a) IT equipment, b) cooling systems, and c) power systems. The energy efficiency of IT equipment has been improved with the development of more energy efficient IT devices, server virtualization and efficient workload distribution across the server racks [1,2]. The energy efficiency of cooling systems has also been improved at multiple scales from individual chips to the cooling towers [3–8]. The proposed energy efficiency enhancement strategies in these areas are capable of reducing rate of increase of electricity demand from DCs from 200% in 2000–2005 period to 56% in 2005–2010 period. However, this rate is still high and accounts for 1.3% of the worldwide electricity consumption [8–10].

The power systems of DCs, on the other hand, have been improved by engineering more energy efficient uninterruptible power supplies (UPSs) and power distribution units (PDUs) and development and integration of sustainable power supply systems. Currently, rapidly depleting non-renewable sources of energy are the main source of power for DCs. These sources, with high production costs and destructive environmental effects, have increased the demand for inexpensive and environmentally friendly alternatives. Renewable sources of energy, such as wind, solar, biofuels, and hydropower, are examples of alternatives which are continuously replenished by natural processes. The cost-effectiveness of renewable energy sources, and their lower greenhouse gas emissions, have increased their utilization in powering DCs.

* Corresponding author.
E-mail addresses: ali.habibi@unimelb.edu.au, a.habibikhalaj@gmail.com (A. Habibi Khalaj).

https://doi.org/10.1016/j.rser.2018.05.006
Received 12 November 2016; Received in revised form 2 May 2018; Accepted 2 May 2018

Nomenclature

a	PV module and wind turbine parameter
A	wind turbine's swept area (m^2), annual capital cost
a_i	vector of coefficients determined from module testing
AM_a	absolute air mass
AOI	solar angel of incident
b	PV module and wind turbine parameter
b_i	vector of coefficients determined from PV module testing
c	wind turbine parameter
C_{batt}	present value of battery (USD)
$C_{conv/inv}$	present value of converter/inverter (USD)
c_i	vector of coefficients determined from PV module testing
C_i	empirical coefficients determined from inverter testing
C_{OM}	operation and maintenance cost for each component (USD)
d	wind turbine parameter
$e_{(t)}$	price of exported electricity from power grid at time t ($\$/kWh$)
E_0	reference solar irradiance (1000 W/m^2)
E_b	beam irradiance on array (W/m^2)
E_d	diffuse irradiance on array (W/m^2)
E_e	effective irradiance (W/m^2)
E_g	ground reflected radiation (W/m^2)
E_{POA}	plane of array irradiance (W/m^2)
f_d	fraction of the diffuse light used by the module
g	wind turbine parameter, gravitational constant
h	height (m)
i	interest rate (%)
$i(t)$	price of imported electricity from power grid at time t ($\$/kWh$)
I_{mp}	array maximum power current (A)
I_{sc}	array short circuit current (A)
I_{sc0}	short circuit current at reference conditions (A)
k	Boltzmann's constant ($1.38066 \times 10^{-23} J/K$), number of wind turbine used in wind farm
$m_{\beta_{Voc}}$	coefficient describing the irradiance dependence on the open circuit voltage temperature
n	empirically determined diode factor, system lifetime (year)
N_s	number of cells in series
P	air pressure, initial capital cost
P_0	reference air pressure (101325 Pa)
P_{AC}	AC power output from the inverter (W)
P_{AC0}	maximum AC power rating for inverter at reference conditions (W)
$P_{B^+}(t)$	price of battery (USD)
$P_{B^-}(t)$	power sent to the battery at time t (W)
P_{batt}	power drawn from the battery at time t (W)
$P_{conv/inv}$	price of converter/inverter ($\$/MW$)
P_{dem}	total power demand of data center (W)
P_{DC}	DC power to the inverter, assumed to be equal to (W)
P_{DC0}	DC power level at which the AC power rating is achieved at the reference conditions (W)
$P_E(t)$	amount of exported electricity from grid at time t (W)
$P_{grid}(t)$	amount of drawn electricity from power grid at time t (W)
P_{in}	power available in a volume of air (W)
$P_I(t)$	amount of import electricity from grid at time t (W) array maximum power output (W)
P_{PV}	power output of PV modules that is equal to P_{AC} (W)
P_r	rated power of wind turbine (W)
P_{s0}	DC power required to start the inversion process (W)
P_{wt}, P_v	power output of wind turbine (W)
P_{wf}	wind power output from a wind farm (W)
q	elementary charge constant ($1.60218 \times 10^{-19} coulomb$)
R	universal gas constant ($8.314\, J/molK$)
$SOC(t)$	state of charge of battery at time t (W)
T_0	reference cell temperature (25 °C)
T_a	ambient air temperature (°C)
T_c	PV cell temperature (°C)
T_m	PV module temperature (°C)
V_{DC}	DC voltage input to the inverter, typically assumed to be equal to V_{mp} (V)
V_{oc}	array open-circuit voltage (V)
V_{mp}	array maximum power voltage (V)
V_w	mean wind speed (m/s)
$V_{w,r}$	mean wind speed at reference height (m/s)
z	hub height of wind turbine (m)
z_0	surface roughness length (m)
z_r	reference height (m)
σ	self-discharge rate of battery

Greek symbols

$\alpha_{I_{sc}}$	normalized temperature coefficient for short circuit current (1/°C)
$\alpha_{I_{mp}}$	normalized temperature coefficient for maximum power current (1/°C)
$\beta_{V_{oc}}$	temperature coefficient for module open circuit
$\beta_{V_{oc0}}$	temperature coefficient for module open circuit voltage at reference irradiance condition
$\beta_{V_{mp}}$	temperature coefficient for module open circuit
θ_A	solar azimuth angle
θ_Z	solar zenith angle
θ_T	tilt angel
$\theta_{T,surf}$	tilt angle of the surface
$\rho(z)$	air density at hub height of wind turbine (kg/m^3)
η_C	battery charge efficiency
η_D	battery discharge efficiency
η_g	efficiency of generator
η_{gb}	efficiency of gearbox
η_{inv}	efficiency of inverter
η_p	wind turbine power coefficient

Abbreviation

ACC	Total annual capital cost (USD), air cooled chiller
ACU	air conditioning unit
AOMC	annual operation and maintenance cost
CF	capacity factor
CRAH	computer room air handler
CRF	capital recovery factor
CS	cooling system
DC	data center
DEC	direct evaporative cooler
DNI	direct normal irradiance (W/m^2)
DHI	diffuse horizontal irradiance (W/m^2)
GHI	global horizontal irradiance (W/m^2)
HP	heat pipe
HW	heat wheel
OA	outside air
ICT	information and communications technology
IEC	indirect evaporative cooler
IT	information technology
PDU	power distribution unit
PV	photovoltaics
RA	return air from data center room
SA	supplied air into the data center room
UH	ultrasonic humidifier
UPS	uninterrupted power supplies
WB	wet-bulb temperature
WCC	water cooled chiller
WS	wind speed