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Optimal design of hybrid renewable energy systems in buildings with low to high renewable energy ratio

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ABSTRACT

We develop a simulation-based meta-heuristic approach that determines the optimal size of a hybrid renewable energy system for residential buildings. This multi-objective optimization problem requires the advancement of a dynamic multi-objective particle swarm optimization algorithm that maximizes the renewable energy ratio of buildings and minimizes total net present cost and CO_2 emission for required system changes. Three proven performance metrics evaluate the quality of the Pareto front generated by the proposed approach. The obtained results are compared against two reported multi-objective optimization algorithms in the related literature. Finally, an existing residential apartment located in a cold Canadian climate provides a test case to apply the proposed model and optimally size a hybrid renewable energy system. In this test application, the model investigates the potential use of a heat pump, a biomass boiler, wind turbines, solar heat collectors, photovoltaic panels, and a heat storage tank to produce renewable energy for the building. Furthermore, the utilization of plug-in electric vehicles for transportation reduces gasoline use where all power is generated by the building, and the utility provides the means to match intermittent renewable generation from solar and wind to the building electrical loads. Model results show that under the chosen meteorological conditions and building parameters a wind turbine, and plug-in electric vehicle technologies are consistently the optimal option to achieve a target renewable energy ratio. In particular, the optimization result shows that the renewable energy ratio can achieve near 100% by installing a 73 kW wind turbine, a 200 kW biomass boiler, and using plug-in electric vehicles. This option has a net present cost of C$705,180 and results in total CO_2 emission of 2.4 ton/year. Finally, a sensitivity analysis is performed to investigate the impact of economic constants on net present cost of the obtained non-dominated solutions.

1. Introduction

In the last decades, fossil fuel consumption and consequently its environmental impact has become a substantial universal concern. The building sector amounts to 40% of total energy demand. Currently, residential buildings are responsible for the major share (70%) of energy consumption in the building sector [1]. Thus, demand and supply side planning is required to decrease the energy demand of buildings and to provide the rest of the energy load with potential renewable resources. In addition, political limitations and state subsidies encourage users to search for environmental friendly solutions [1,2]. The concept of Zero Energy Building (ZEB), which is expected to be the future perspective of buildings design has become a worldwide issue over the last decade [2]. ZEB are defined as buildings whose annual energy requirement is supplied purely by renewable energy sources (RES) [1]. Therefore, ZEB can be stated as master plan for increasing the renewable energy ratio (RER). RER is defined as the amount of renewable energy generated divided by the total primary energy used.

The cost of renewable energy technologies can be attractive in the case of wind and solar—their intermittent nature makes them more difficult to integrate to the grid. Hence, optimal sizing of a building renewable energy supply system can significantly impact its economic performance and consequently its reliability. In the design stage of a building energy supply system, many aspects have to be considered including economic performance, environmental impact, and reliability issues. In other words, decision makers, who are in charge of building energy system design, must make a trade-

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Nomenclature

$A_{Land,b}$	required land for biomass production [m^2]
A_{Max}	upper limit for building roof area [m^2]
A_{PV}	area of PV panel installed on the building roof [m^2]
A_{SC}	area of solar collector installed on the building roof [m^2]
A_r	wind turbine rotor swept area [m^2]
$Biomass_{Max}$	annual available biomass [ton/year]
C	coverage metric
$C_{b,Col}$	biomass collection cost [C$/ton]
$C_{b,St}$	biomass storage cost [C$/ton]
$C_{b,Tr}$	biomass transportation cost [C$/ton.km]
$C_{elec,s}$	sold electricity price [C$/kWh]
$C_{elec,b}$	purchasing electricity price [C$/kWh]
C_{Gas}	gasoline price [C$/litre]
$C_{I,j}$	capital cost of component j [C$/unit]
C_{NG}	natural gas price [C$/m^3]
C_P	wind turbine power coefficient
$C_{O\&M,j}$	operation & maintenance of component j [C$/unit]
$C_{rep,j}$	replacement cost of component j [C$/unit]
CO_{AR}	cooling load provided by air refrigerators [kWh]
CO_{HP}	cooling load provided by heat pump [kWh]
COP_{AR}	coefficient of performance for air refrigerator
COP_{HP-CO}	coefficient of performance of heat pump in cooling mode
COP_{HP-HE}	coefficient of performance for heat pump in heating mode
CRF	capital recovery factor
E_{EX}	excess electricity [kWh]
E_{bought}	bought electricity [kWh]
E_{AR}	electricity consumption by air refrigerator [kWh]
$\mathrm{E_{EV}}$	electricity consumption by PEV [kWh]
E_{HP}	electricity consumption by heat pump [kWh]
E_{Sold}	sold electricity to the grid [kWh]
$\mathrm{E_{PV}}$	net power generated by PV panel [kWh]
$\mathrm{E_{PV-Re}}$	PV panel power output [kWh]
$\mathrm{E_{PVR-Re}}$	rural PV panel power output [kWh]
$\mathrm{E_{WT}}$	net power generated by Wind turbine [kWh]
$\mathrm{E_{WT-Re}}$	wind turbine power output [kWh]
EF_E	emission factor of grid electricity [kg CO_2/KWh]
EF_{Gas}	emission factor of gasoline [kg/lit]
EF_{NG}	emission factor of NG [kg CO_2/m^3]
$El_{b,y}$	annual electricity bought from the grid [kWh/year]
$El_{s,y}$	annual sold electricity [kWh/year]
P_{WT}	wind turbine capacity [kW]
S	spacing metric
T	project life time [year]
$T_{ambeint,hr}$	hourly ambient temperature [°C]
$T_{d,cool}$	summer design temperature [°C]
$T_{d,heat}$	heating design temperature [°C]
T_{ewt}	entering fluid temperature in HP [°C]
T_g	ground temperature [°C]
$T_{SC,in}$	solar collector water input temperature [°C]
t_{zone}	time zone difference
U_{loss}	solar collector heat loss coefficient [W/m^{2}K]
$Un_{Cooling}$	hourly unmet cooling energy [kWh]
Un_E	hourly unmet electricity [kWh]
Un_{HE}	hourly unmet heating [kWh]
Un_{HW}	hourly unmet hot water [kWh]
V_C	wind turbine cut-in wind speed [m/s]
V_f	wind turbine cut-off wind speed [m/s]
V_r	wind turbine rated wind speed [m/s]
$W_{com,max}$	compressor capacity [kW]
Z	wind turbine hub height [m]
EOT	equation of time [min]
GAS	hourly gasoline consumption [kWh]
Gas_y	annual gasoline consumption [lit/year]
HE_{Bio}	heating load provided by biomass boiler [kWh]
HE_{HP}	heating load provided by heat pump [kWh]
HE_{NG}	heating energy generated by NG boiler [kWh]
HHV_b	higher heating value of biomass [Mj/kg]
HHV_{Gas}	higher heating value of gasoline [Mj/kg]
HHV_{NG}	higher heating value of NG [Mj/kg]
$HP(t)$	hourly heat pump energy output [kWh]
$HST(t)$	level of hot water in storage tank in time step t [kWh]
$HW_{Bio-tank}$	hot water load provided by a biomass boiler [kWh]
$HW_{HP-tank}$	hot water load provided by heat pump [kWh]
$HW_{NG-tank}$	hot water generated by NG boiler [kWh]
$HW_{SC-tank}$	hot water generated by SC [kWh]
HW_{T-load}	total hot water sent to load [kWh]
i	interest rate [%]
$I_{b,n}$	direct normal irradiance [kWh/m^2]
$I_{b,tilt}$	beam radiation [kWh/m^2]
$I_{d,tilt}$	sky diffuse radiation [kWh/m^2]
$I_{r,tilt}$	ground reflected solar radiation [kWh/m^2]
I_T	total solar radiation on tilted surface [kWh/m^2]
K	single payment present worth
$L_{Cooling}$	cooling demand [kWh]
L_{HE}	heating demand [kWh]
L_{HW}	hot water demand [kWh]
L_{local}	local longitude [degree]
LLP_{max}	loss of load probability upper limit [%]
LLP	loss of load probability[%]
LST	local standard time
m_b	biomass flow rate [kg/hr]
MS	maximum spread metric
NG_y	annual NG consumption [m^3/year]
P_{Bio}	biomass boiler capacity [kW]
$\mathrm{P_{j,max}}$	upper limit of the capacity of components
$\mathrm{P_{j,min}}$	lower limit of the capacity of components
P_{HP}	heat pump capacity [kW]
P_{HST}	heat storage tank capacity [m^3]
P_{SC}	solar collector capacity [kW]
P_r	wind turbine rated output power [kW]
RER	renewable energy ratio [%]
η_{pv}	PV panel efficiency [%]
η_{SC}	solar collector efficiency [%]
η_{bb}	biomass boiler efficiency [%]
η_{In}	inverter efficiency [%]
η_{NGb}	natural gas boiler efficiency [%]
η_{Re}	rectifier efficiency [%]
$\varepsilon_{Tr,gas}$	transportation allocation coefficient of gasoline car
$\varepsilon_{Tr,PEV}$	transportation allocation coefficient of PEV
$\varepsilon_{CO,AR}$	cooling allocation coefficient of air refrigerator
$\varepsilon_{CO,HP}$	cooling allocation coefficient of heat pump
$\varepsilon_{HE,bb}$	heating and hot water allocation coefficient of biomass boiler
$\varepsilon_{HE,HP}$	heating and hot water allocation coefficient of heat pump
ξ	sun azimuth angle [degree]
ε	tilt angle [degree]
λ	latitude [degree]
δ	solar declination angle [degree]
χ	zenith angle [degree]
ζ	plate azimuth angle [degree]
ρ	air density [kg/m^3]