



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 CO₂ 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 CO₂ 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.

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

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