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Optimal design of energy and water supply systems for low-income communities involving multiple-objectives

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ABSTRACT

This paper proposes the use of Combined Heat and Power systems for providing water and energy, and thermal and electric utilities, in geographically isolated communities, where the interconnection with the grid is not available. A common design practice is to implement different energy storage technologies, usually batteries, for reducing the gap between energy generation and electric consumption. However, in communities with low incomes, it is not possible to use batteries due to the high capital costs. This work presents a new approach for providing simultaneously electricity and water using the fresh water extraction and storage for reducing the gaps between generation and consumption. The proposed approach is based on a mixed integer nonlinear programming formulation, which accounts for the optimal selection of multiple combined heat and power technologies and the sizing of the water storage and pumping technologies. A multi-objective analysis is presented considering as objective functions the economic costs and environmental impact associated with the space used by the system and water consumption. A community in the mountains of Mexico is presented as case study. The results show that it is possible to provide energy and water at low costs and reducing the environmental impact, reaching a trade-off between the considered objective functions.

1. Introduction

The economic and technological developments have generated multiple satisfiers to society. One of the most important is the electric power supply. According with data of The World Bank, by 2012 around 85% of the world population had access to electricity [1]. It means that there are communities that do not have electric utilities. The main reasons why these populations lack elementary energy utilities are varied. First, the geographical conditions that make difficult to interconnect to the grid isolated communities [2]. Furthermore, sometimes the needed energy is not significant from an economic point view, and to expand the grid to some far locations results in a non-profitable investment [3]. In developing countries, these conditions are remarkable, especially in rural areas where there is concentrated most of the population without access to energy utilities [4]. The situation of these communities is complicated considering the low-income of the local population and the lack of other basic utilities (i.e., water) [5]. A water pumping system is the typical used approach to extract, transport and supply water; but, its operation is limited by the availability of energy sources. In addition, low-income communities frequently have not enough economic resources for covering the costs associated to pumping, and frequently it is needed to transport the water from remote places [6]. Considering this background, integral energy systems capable to provide water and energy at low costs are needed for solving the situation of these isolated communities.

The off-grid and island operation of energy systems have been addressed using technologies based on renewable sources or conventional systems as wind [7], solar [8], wave [9], solar-wind [10], Combined Heat and Power (CHP) [11], biofuels [12], Rankine cycles [13] or hybrid systems using multiple technologies [14]. Despite the development of these systems, it is possible to detect at least two significant problems for implementing the off-grid systems in low income and isolated communities. The first one is the availability of renewable resources, which depends on the geographic conditions. In regions with not significant bio-resources available, or wind or solar low potentials, it is not profitable the use of renewable technologies [15]. This fact leads to the second factor, which corresponds to the low income of the community. Some distributed energy technologies are significantly expensive, even though their efficiency, for applying in low income communities, it is a remarkable problem in developing countries [16]. Batteries have become in the core of the energy storage on off-grid systems, reducing the gaps between the energy generation and consumption [17]. However,

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Nomenclature

Variables

Symbol	Description (units)
A	convective area (m^2)
$CCost$	capital cost ($)
$Cost$	operative cost ($)
CS	compromise solution
E	electric energy (kWh)
F	fuel flux [kWh]
f	partial load function
G	water flux [kg]
HS	heat sales [$]
PL	partial load
Q	heat flux [kWh]
S	land used by the equipment [m^2]
SW	water consumption
T	temperature [°C]
TAC	total annual cost
V	volume [m^3]
W	electric flux [kWh]
WSP	sales of electricity for pumping [$]
WS	water sales [$]
WSH	sales of electricity to the households [$]
y	existence of equipment (binary)
α	scaling factor for an objective function
η	efficiency

Parameters

Cp	specific heat [kWh/kg °C]
g	gravity constant [m/s^2]
H_D	operative days [days]
k_F	annualization factor
U	convective coefficient [kWh/m^2 °C]
UCF	unitary cost of fuel [$/kWh]
UCW	unitary cost of external water [$/kg]
UCWT	unitary cost of water treatment [$/kg]
UPH	unitary price of heat from the CHP system [$/kWh]
UPP	unitary price of electricity for pumping [$/kWh]
UPW	unitary price of electricity from the CHP system [$/kWh]
UPWT	unitary price of water supply [$/kg]
VC	variable cost [$]
Δz	height difference between the water source and the fresh water storage tank [m]
β	factor for the economies of scale
δ	units conversion factor
ρ	water density [kg/m^3]
σ	land used by the technology [m^2/kWe or m^2/m^3]
ω	weight, level of importance or preference for an objective function

Acronyms

amb	ambient
CHP	Combined Heat and Power
D	demand
ext	external water supply
Fuel	fuel
FC	fuel cell
FW	fresh water
FWST	fresh water storage tank
GHGE	greenhouse gas emissions
H	households
HW	hot water
ICE	internal combustion engine
L	convective losses
LB	lower bound
LW	local water (from FWST)
MAX	maximum
MIN	minimum
MT	microturbine
NG	natural gas
NS	nadir solution
OM	operating and maintenance
P	pumping system
Pur	purge
R	water used for regulating temperature
SE	stirling engine
TST	thermal storage tank
T	total
UB	upper bound
UP	utopia point
WT	water treatment

Sets

t	time periods [h]
s	seasons (spring, summer, fall, winter)
Φ	CHP technologies (ICE, FC, MT, SE)

their costs and environmental impacts reduce the convenience of using them in communities limited by economic resources [18].

Combined Heat and Power systems (CHP) have a flexible implementation due to the use of conventional fuels (including coal, natural gas, diesel and biofuels). Therefore, they do not depend on the environmental and climatic conditions associated to the renewable resources as wind, solar, geothermal or hydro systems [19]. The recent advantages in shale gas exploitation have reduced the natural gas costs [20]. Also, the use of bio-fueled CHP plants can stimulate the local production of biofuels [21]. Environmental policies have developed economic incentives for implementing technologies based on decentralized energy systems, as CHP systems, for controlling the pollution and to promote the economic development of disenfranchised communities [22]. In addition, the design of small domestic CHP plants with a low operating cost has been addressed in recent works for interconnected systems [23] and for bio-fueled CHP systems [24].

For solving the electric storage problem, avoiding the battery costs, in big centralized energy systems (as hydroelectric plants), pumped water (obtained by using the surplus of energy) is stored as an upstream for using later [25]. The fundamental principle of pumped hydroelectric storage is to store electric energy in the form of hydraulic potential energy [26]. However, the concept of polygeneration, as the use of multiple fuels with simultaneous delivery of several utilities, leads to the use of pumped water as domestic water and to consider it as a by-product in small domestic CHP plants. This strategy can mitigate the problems of water and energy supply inherent to low-income isolated communities.

The design of polygeneration energy systems involves several issues, including the optimal selection of prime movers [27], sizing of the system [28], determining capital and operating costs [29], provide energy demand profiles [30] and to account for the environmental impact [31]. Recent works have focused on the water consumption in centralized systems [32]. This problem, water-energy nexus, needs to be considered on distributed energy systems as CHP units [33,34].

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