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Energy performance assessment of a polygeneration plant in different weather conditions through simulation tools

S. Soutullo[a,*], L.A. Bujedo[b], J. Samaniego[b], D. Borge[c], J.A. Ferrer[a], R. Carazo[c], M.R. Heras[a]

[a] Department of Energy, Energy Efficiency in Buildings Unit, CIEMAT, Madrid E-28040, Spain
[b] Energy Division, CARTIF Foundation, Parque Tecnológico Boecillo, E-47151 Valladolid, Spain
[c] Ideas TX Ingenieria, Research & Development Area, 5 Del Sol Street, First floor, E-49800 Toro, Spain

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ABSTRACT

This paper analyzes theoretical dynamic performance of centralized polygeneration technologies using district networks as distribution system. Three Spanish cities have been studied using as input variables Typical Meteorological Years (TMY), representative local constructions and normative internal loads for residential and tertiary buildings. Energy simulation has been carried out with the software TRNSYS. Different dynamic models that connect renewable and conventional technologies have been developed to represent the thermal and electrical performance of a polygeneration plant. The thermal model is based on the combined operation of solar thermal collectors and biomass boilers using cogeneration systems as a backup when both renewable technologies cannot supply the thermal district loads. The electrical model is based on the independent operation of photovoltaic panels and wind turbines in combination with Polymeric Electrolyte Membrane (PEM) fuel cells. Global systems work at their limit operation to compare the final results of the three cities. Different configurations have been studied to evaluate the annual thermal and electrical coverage reached by the plant. Once optimized the area of the solar field the energy fraction covered by the renewable systems increases logarithmically with the power of the biomass boilers. The simultaneous operation of photovoltaic panels and wind turbines to feed PEM cells maximize the electrical coverage achieved by the district. Results of both simulation models show that for all weather conditions studied, the optimal solution is a combined operation of the renewable technologies used.

1. Introduction

In the last years, over 50% of the world population has moved to the cities leading to an increase of the urban consumption up to two-thirds of the total produced energy. The European Union is committed to handle this problem through the implementation of several programs, platforms and directives to reduce this increasing energy trend. In this line the Framework Programme for Research and Innovation [1], the European directives of energy efficiency in urban areas [2] and the European Technology Platform for Power Networks of the Future or the EERA Alliance [3], promotes the development of clean, safe and efficient sources of energy for intelligent Cities and Communities [4].

Effective implementation of the European energy efficiency directives supposes great efforts at all stages of the energy chain: from the transformation of energy and its distribution to its final consumption. To achieve these requirements, all the countries have to develop policies to improve the building renovation, maximize the efficiency of grids and infrastructures, promote the use of high-efficiency cogeneration and district heating and cooling or maximize the renewable share into the energy market. In Spain, the energy import dependency (70.5%) is much higher than the mean of the European Union (53.2%). The highest producers of renewable energy within the European Union were Germany, Italy and France, with percentages of 17.5%, 12.2% and 12% respectively. Spain has a production of 9.1% of renewable energy.

The Spanish share of the gross inland consumption of energy of the European Union is about 7.1% [5]. This situation has forced to analyse alternative systems to reduce the energy demand. These models should consider efficient generation with local energy distribution. An efficient generation need to include renewable technologies to reduce the fossil fuels dependence and improve the environmental behaviour of the whole system. A local distribution considers the consumption point near to the source of generation,

* Corresponding author.
E-mail address: silvia.soutullo@ciemat.es (S. Soutullo).

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Nomenclature

TMY	Typical meteorological year
TRNSYS	TRaNsient systems simulation program
PEM	Polymeric Electrolyte Membrane
EERA	European energy research alliance
HDD_{18}	Heating degree days (base temperature 18 °C)
CDD_{18}	Cooling degree days (base temperature 18 °C)
CTE	Spanish technical building code
IDAE	Institute for energy diversification and saving ascribed to the spanish ministry of economy
ORC	Organic Rankine Cycle
DEGS	Diesel engine generation set
PV	Photovoltaic

Symbols

η	Efficiency [–]
a_0	Intercept of the collector efficiency [–]
a_1	First order coefficient in the collector efficiency equation [kJ/hm^{2}K]
a_2	Second order coefficient in the collector efficiency equation [kJ/hm^{2}K^2]
Tf	Inlet temperature of fluid [K]
Ta	Ambient temperature [K]
G	Global radiation incident on the solar collector [kJ/hm^2]
$Q_{exhaust}$	Energy exhaust from the boiler [kJ/h]
Q_{fuel}	Rate at which the fuel energy is consumed [kJ/h]
$\eta_{combustion}$	Combustion efficiency of the boiler [–]
M_i	Mass of fluid in the i node of the tank
C_p	Specific heat of the tank fluid [kJ/kgK]
T_i	Temperature in i node of the tank [°C]
$\dot{m}_{hi}$	Inlet flow stream [kg/h]
$\dot{m}_{ho}$	Outlet flow stream [kg/h]
P_{TOT}	Output total power of DEGS [W]
N_{DEGS}	Number of DEGS [–]
P_{DEGS}	Rate electrical power per one DEGS unit [W]
Capacity	Capacity of the absorption machine [kJ/h]
$f_{FullLoadCap}$	Fraction of the full load capacity during the operation under simulation conditions [–]
f_{NomCap}	Fraction of the nominal capacity during the operation under simulation conditions [–]
$Capacity_{Rated}$	Rated cooling capacity of the absorption machine [kJ/h]
COP	Coefficient of performance [–]
P_{MAX}	Maximum power of the photovoltaic array [W]
I_{MAX}	Maximum current [A]
V_{MAX}	Maximum voltage [V]
P	Output power of the wind turbine [W]
Cpw	Power coefficient of the wind turbine [–]
ρ	Air density [kg/m^3]
A_R	Area of the rotor [m^2]
U_0	Velocity in the free stream [m/s]
P_{cell}	PEM Stack power [W]
U_{cell}	Voltage of each cell [V]
I_{FC}	Total fuel cell current [A]
U_{TN}	Thermoneutral voltage [V]

so the impact area should be neighborhoods or districts. To optimize the energy and economic performance of these distributed plants, many technologies should be used to supply the cooling, heating and electrical demands of the analyzed area [6–8].

Currently different solutions have been studied taking into account environmental, social, energy and economics aspects of polygeneration and distributed systems [9]. In this context, the Spanish INNPACTO DEPOLIGEN Project [10] represents a case study that quantify the theoretical potential of centralized polygeneration plants composed by renewable systems, avoiding the connexion with conventional installations and electrical grids. This project investigates many configurations that combine the reduction of energy demands, by means of more efficient buildings, with the optimization of the energy consumption, by means of renewable, distributed and centralized systems. With this purpose, the main objective is analysing the viability of using installations and storages fed by renewable sources to generate the energy demanded by a generic district.

Plants composed by many generation sources to supply the cooling, heating and electrical demands (polygeneration plants), have higher exergy efficiency than conventional systems due to the annual waste heat utilization. The coupling of these thermodynamic processes reduces the environmental impact and increases the overall system efficiency optimizing the use of primary energy. Polygeneration is a form of distributed energy production with significant savings thanks to the reduction of losses in the transmission of energy, estimated at over 60% for heat dissipation before end user [7,11]. Future polygeneration distributed plants should consider efficient buildings and sustainable systems based on integrated renewable technologies that minimize the energy losses and cost, maximize the efficiency factors and the heat recovered as well as optimize the integration of intelligent controls and the adjustment between demand and production [12].

This paper develops a theoretical simulation methodology to analyse the energy performance of a polygeneration plant to supply the thermal and electrical loads of three districts, placed in different cities of Spain: Oviedo, Seville and Zamora. The application of this methodology has generated two new dynamic TRNSYS simulation projects, one to supply the thermal demands of the districts and another for the electrical loads. Both simulation projects have been connected between them through the operation of cogeneration systems.

The major contribution of these models is the combined management of all the generation technologies with the aim of optimizing the use of renewable systems and minimizing the energy surpluses. The regulation of each technology is based on the availability of the natural resources and the energetic performance of each district.

2. Simulation methodology to analyse a polygeneration plant

There are many existing energy tools that are used to quantify the integration of renewable installations into a polygeneration plant [13]. The election of one of them depends on the objectives of the project as well as the initial data. In this case, the overall objective of the project is the development of a global theoretical model that allows the evaluation of the energy performance over a specific period of time, the determination of the critical points, the calculation of the operation curves and the energy optimization of the system. With this objective, dynamic simulation programs are presented as excellent tools to quantify different operation scenarios of given systems to supply the energy demands modelled [14–18].

A dynamic polygeneration project should take into account the generation and distribution of energy as well as the energy exchanges produced during the system operation. These processes are time-dependent due to fluctuations generated by external and internal excitations, so numerical equations of each element should consider the time dependence. Finally, all the elements of the system are coupled between them, so the energy balances cannot be calculated independently. With these assumptions a polygenera-