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ScienceDirect

Energy Procedia 91 (2016) 517 – 527

Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

Cost-optimal sizing of solar thermal and photovoltaic systems for the heating and cooling needs of a nearly Zero-Energy Building: design methodology and model description

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Abstract

This paper deals with the cost-optimal sizing of solar technologies for thermal and electrical needs of residential or tertiary nearly Zero-Energy buildings. The proposed design procedure is based on lifetime simulation of building loads and energy systems; therefore, according to proper cost-optimality considerations, it is possible to find the best sizing of both heat and electricity generators in the context of high-efficiency buildings (e.g. number of solar thermal and PV modules). The paper is divided in two parts. In this first part, we describe general features and principles of the methodology, together with the physical models of building-plant system. Building requirements of thermal and electrical energy are evaluated according to internal loads and external climate, while energy system operation is simulated by a full set of equations reproducing the coupled behavior of each piece of equipment. A preliminary application example referring to a nearly Zero-Energy Building is also illustrated: In the second part of the work, we will apply and discuss the overall simulation-based optimization procedure. Results show the notable benefits of the proposed design approach with respect to traditional ones, in terms of both energy and economic savings. Besides, the proposed methodology can be successfully applied in the more general framework of Net Zero Energy Buildings (NZEBs) in order to fulfill recent regulatory restrictions and objectives in building energy performances.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: Nearly Zero-Energy Buildings; cost-optimal design; solar thermal; photovoltaics; heat pumps; design method

1. Introduction

The design of building energy systems aims to figure out the best technological solution to match energy demand for services. A universal straightforward design procedure does not exist as any specific project has particular characteristics and objectives [1].

1876-6102
Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.191

Nomenclature

Acronyms

B.O.S. balance of system
DHW domestic hot water
H/C heating and cooling system
HP heat pump
PV photovoltaic system
RF radiant floor
ST solar thermal system
TS thermal storage

Symbols

C global cost
C_0 installation cost
C_{dehum} coil characteristic coefficient
COP actual coefficients of performance in heating mode
COP_{id} maximum theoretical COP in heating mode (i.e. Carnot efficiency)
E energy
EER actual coefficients of performance in cooling mode
EER_{id} maximum theoretical EER in cooling mode (i.e. Carnot efficiency)
F_R ST removal factor
H_{ve} equivalent ventilation-thermal transmittance
I_{sol} global irradiance at a given orientation
$I_{sol,o}$ extra-terrestrial global irradiance on the horizontal surface
K_{RF} RF thermal output per surface unit
K_t hourly clearness index
$NOCT$ nominal operating cell temperature
P power
S surface
T_{aqu} aqueduct temperature
T_{DHW} DHW delivery temperature
$T_{eva/cond}$ effective heat exchange temperature in HP evaporator or condenser
T_{ext} outdoor temperature
T_{off} switching-off temperature
T_{PV} PV modules temperature
T_{TS} thermal storage temperature
U_L ST frontal losses coefficient
U_{wf} water-floor thermal transmittance
UA heat transmittance-surface product
V volume
b_0 incidence angle modifier coefficient for single-cover ST collectors
c specific heat capacity
c_0 unitary installation cost
f_p primary energy factor
n number of PV modules or ST collectors
n_{air} air changes per hour
n_{RF} emitter exponent of the radiant floor
s thickness
x humidity ratio

Greek letters

$\beta_{T,PV}$ PV penalization factor depending on PV technology
η efficiency
ϑ angle between the beam radiation and the normal to the ST collectors
λ thermal conductivity
ρ density
$(\tau\alpha)_n$ transmittance-absorptance product for normal-incidence irradiance
ϕ time shift

Superscript

II second-law parameter
' next time step
* sol-air temperature
TOT cumulative value at the end of project lifetime

Subscript

CK cooking service
LGT lighting
OU electric uses (household appliances, office devices)
$dehum$ dehumidification
des design condition
el electrical
$grid$ electrical grid
in inlet conditions
inv electronic converter (i.e. B.O.S.)
ls losses
$prod$ production
ref reference conditions
th thermal
w water
z indoor