Applied Energy 181 (2016) 549–561

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Enhanced thermal energy supply via central solar heating plants with seasonal storage: A multi-objective optimization approach

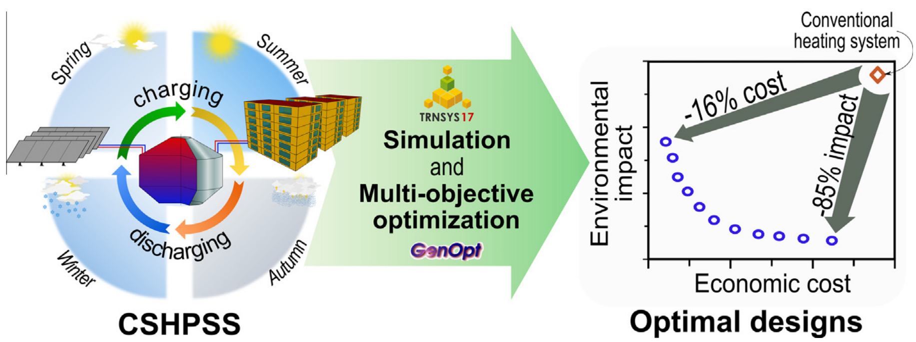
Victor Tulus [a], Dieter Boer [b,*], Luisa F. Cabeza [c], Laureano Jiménez [a], Gonzalo Guillén-Gosálbez [a,d]

[a] Departament d'Enginyeria Química, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain
[b] Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain
[c] GREA Innovació Concurrent, Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain
[d] Department of Chemical Engineering, Centre for Process Systems Engineering, Imperial College, South Kensington Campus, SW7 2AZ London, UK

HIGHLIGHTS

- A central solar heating plant with seasonal storage (CSHPSS) is examined.
- A systematic approach for multi-objective optimization of CSHPSS is developed.
- A TRNSYS simulation is optimized in combination with life cycle analysis principles.
- The capabilities of the approach are tested through a case study in Barcelona, Spain.
- Well-designed CSHPSS can bring economic and environmental benefits simultaneously.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form 5 August 2016
Accepted 6 August 2016

Keywords:
Central solar heating plant with seasonal storage
Thermal energy storage
Solar district heating
Multi-objective optimization
Life cycle assessment
TRNSYS modelling

ABSTRACT

Central solar heating plants with seasonal storage (CSHPSS) are among the most promising technologies to save energy in the industrial and residential-commercial building sectors. This work introduces a systematic approach to optimize these systems according to economic and environmental criteria. Our method, which combines the TRNSYS 17 simulation software with life cycle assessment and multi-objective optimization, identifies optimal CSHPSS designs for any climatic condition and heating demand profile considering economic and environmental criteria simultaneously. The capabilities of this approach are illustrated through its application to a case study of a CSHPSS located in Barcelona (Spain), which satisfies a heating demand for a neighborhood of 1120 dwellings. Numerical results show that the CSHPSS plant leads to significant environmental and economic improvements compared to the use of a conventional natural gas heating system. Our tool can guide engineers and architects in the transition towards a more sustainable residential sector.

1. Introduction

Due to their high specific energy density and combustion temperatures ranging from 1000 to 2500 °C, fossil fuels are excellent energy carriers able to meet extreme energy demands. Unfortunately, large amounts of fossil fuels are used inefficiently to cover

* Corresponding author.
E-mail addresses: victor.tulus@urv.cat (V. Tulus), dieter.boer@urv.cat (D. Boer), lcabeza@diei.udl.cat (L.F. Cabeza), laureano.jimenez@urv.cat (L. Jiménez), g.guillen05@imperial.ac.uk (G. Guillén-Gosálbez).

http://dx.doi.org/10.1016/j.apenergy.2016.08.037
0306-2619/

Nomenclature

A_{COL}	total aperture area of the solar collectors (m^2)
$A_{HE1(HE2)}$	heat transfer area of the heat exchanger 1 or 2 (m^2)
ADR	ratio between the area of solar collectors and the total heating demand (m^2/(MW h/year))
CAP_k	design variable of equipment unit k
C_{AUX}	annual operation cost of auxiliary heater(€)
C_C	initial capital cost (€)
$CEPCI^{year\ A}$	Chemical Engineering Plant Cost Index in base year (–)
$CEPCI^{year\ B}$	Chemical Engineering Plant Cost Index in installation year (–)
c_E	cost of electricity (€/kW h)
c_F	cost of natural gas (€/kW h)
C_M	annual cost of equipment maintenance (€)
C_O	total discounted operating cost (€)
C_P	annual operation cost of pumps (€)
C_R	total discounted equipment replacement cost (€)
d	market discount rate (%)
DAM_d	indicator result for damage category d
FBM_k	bare module factor of equipment unit k (–)
$f_c(x)$	original objective function [$NPC(x)$ or $RCP(x)$]
$\bar{f}_c(x)$	normalized objective function [$NPC(x)$ or $RCP(x)$]
f_m	maintenance factor (–)
$f^{PN}(x)$	pseudo nadir point
$f^{UT}(x)$	utopia point
i	annual inflation rate (%)
i_e	annual electricity inflation rate (%)
i_f	annual natural gas inflation rate (%)
IMP_e	indicator result for endpoint impact category e
L_{AUX}	annual natural gas load consumed by the auxiliary heater (MW h)
LCI_i^{MP}	life cycle inventory of the elementary flow i related to manufacturing process
LCI_i^{OP}	life cycle inventory of the elementary flow i related to operation activities
LCI_i^{TOT}	total life cycle inventory of the elementary flow i
LCI_i^{TR}	life cycle inventory of the elementary flow i related to transportation
L_P	annual electricity load consumed by pumps (MW h)
$\dot{m}_{P_1\ (P_2\ or\ P_3)}$	mass flow rate pumped through P_1, P_2 or P_3 (kg/h)
N_e	period of economic analysis (year)
NPC	net present cost of CSHPSS (€)
PEC_k	purchase cost of the equipment unit k in installation year (€)
$PEC_k^{year\ A}$	purchase cost of the equipment unit k in base year (€)
PVF_n	present value factor of a single future cash flow at the beginning of n^{th} time period (–)
PWF	present worth factor of periodic future cash flows (–)
Q_{AUX}	duty of auxiliary heater (kW)
RCP	ReCiPe 2008 aggregated impact factor (Pt)
t	time period (h)
V_{TEST}	volume of the thermal energy storage tank (m^3)
VAR	ratio between the volume of storage tank and the area of solar collectors (m^3/m^2)
$WS(x)$	weighted-sum objective function (–)
x	continuous variables of the simulation model
x^L	lower bounds of the continuous variables of the simulation model
x^U	upper bounds of the continuous variables of the simulation model
α_{CF}	factor of contingency charges and fees (–)
α_k	purchase cost coefficient of equipment unit k
β_k	purchase cost exponent of equipment unit k (–)
δ_d	normalization factor for damage category d
θ_{ei}	characterization factor that connects the elementary flow i with endpoint impact category e
λ	non-negative weight for the weighted-sum method
ξ_d	weighting factor for damage category d

Abbreviations

AUX	auxiliary heater
COL	solar collector
CHP	combined heat and power
CSHPSS	central solar heating plant with seasonal storage
DH	district heating
GenOpt	generic optimization program
GPSPSOCCHJ	generalized pattern search algorithm with particle swarm optimization with construction coefficient and Hooke-Jeeves algorithm
HE	heat exchanger
HJ	Hooke-Jeeves algorithm
LCA	life cycle assessment
MOO	multi-objective optimization
P	centrifugal pump
PSO	particle swarm optimization algorithm
TES	thermal energy storage
TEST	thermal energy storage tank
TRNSYS	transient system simulation program

Indices

c	objective function
d	damage category
e	endpoint impact category
i	elementary flow
k	equipment unit

Sets

ID_d	set of endpoint impact categories e that contribute to damage d

energy demands below 260 °C [1], a large fraction of which belongs to the residential-commercial sector. According to the European Environment Agency, in 2013 this sector represented 40% of the total final energy consumption [2]. In order to improve energy efficiency, buildings should use alternative energy sources, particularly for space heating.

Over the past decades, various technologies based on renewable energy sources have been put forward as viable alternatives to the use of fossil fuels, including wind power, hydropower, waste energy, geothermal energy, bio energy, solar energy and energy storage. In the residential-commercial sector, and especially in large cities or inner city areas, these technologies can become even more competitive if they are integrated in an existing district heating (DH) network [3]. Several authors have investigated the use of renewables in the residential sector. Ostergaarg and Lund studied a geothermal energy based technology coupled to a DH network [4], concluding that in combination with an absorption heat pump it could be a promising technology in the short-term. Nuytten et al. assessed the flexibility of a combined heat and power (CHP) system with thermal energy storage (TES) for DH [5]. Sartor et al. developed a simple model of a CHP plant connected to a DH [6]. Wang et al. optimized a CHP-DH plant combined with energy storage