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Multi-objectives, multi-period optimization of district energy systems: III. Distribution networks

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ABSTRACT

A systematic procedure including process design and integration techniques for designing and operating energy distribution networks, and for transportation of resources is presented in this paper. In the developed model a simultaneous multi-objectives and multi-period optimization is principally investigated. In addition to optimize the transportation of resources/products, the proposed method helps decision makers to decide; which type and size of poly-generation technologies, centralized or decentralized, are best suited for the district, where in the district shall the equipment be located (geographically), how the services should be distributed, and what are the optimal flow, supply and return temperatures of the distribution networks. The design and the extension of distribution networks and transportation of resources, based on the geographical information system (GIS), are the novelties of the present work.

1. Introduction

In the perspective of increasing the share of renewable energies, global warming mitigation and with respect to the issue of sustainable energy development, a district energy system, joined with poly-generation technologies, has been considered as a promising option (Weber, Maréchal, & Favrat, 2007).

In the district energy system there are three main challenges; on environmental aspect, on energy efficiency and on economic aspect. The complexity consists in supplying clean energy, consuming fewer fossil resources and finding appropriate solutions to reduce the emissions while also satisfying the energy requirement. Therefore, a systematic procedure is needed to optimize the design and the operation of the district energy system together with optimizing the size and the layout of physical distribution networks and logistics which is taking into account environmental burdens and costs simultaneously.

Multiple research studies have been carried out for simulation and optimization of individual conversion technologies. It is referred to Connolly, Lund, Mathiesen, and Leahy (2010) for a detailed review. The role of design optimization techniques in power generation is also reviewed by Bazmi and Zahedi (2011). Centralized and decentralized technologies are relatively well understood today but the supply side is not the only elements of district energy systems. To enhance a sustainable energy system a number of issues need to be addressed and optimized simultaneously; such as distribution networks' layout, costs, fuel availability, renewable sources, environmental impacts and energy demand fluctuation.

Focusing on purely economic indicators for designing energy systems, has already been under taken by the majority of optimization studies. Cardona, Sannino, Piacentino, and Cardona (2006) applied mono-objective linear programming with boundary constraints related to the secondary objectives for energy saving in airports. Ziher and Poredos (2006) also used the same approach for analyzing the tri-generation system in a hospital, while Arcuri, Florio, and Fragiacomo (2007) applied a mixed integer programming model with ϵ constraint. Casisi, Pinamonti, and Reini (2009) proposed a mixed integer programming model to optimize a distributed cogeneration system with a district heating network. A mixed integer linear programming (MILP) for optimizing the preliminary design of combined heat, cooling and power systems with thermal storage is presented by Lozano, Ramos, and Serra (2010). Selection and sizing of technologies in a poly-generation scheme are investigated with nonlinear programming (Rubio-Maya, 2009; Rubio & Uche, 2011). Haesen, Driesen, and Belmans (2006) introduced a methodology for long-term planning of district energy systems (DES) placement with multi objectives approach.

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Nomenclature

MILP	mixed integer linear programming
MOO	multi objective optimisation
TES	the thermo-economic simulation
EIO	the energy integration optimization
EE	the environomic evaluation
$F_s^{\min/\max}$	equipment's feasible ranges
$T_{min/max}$	feasible ranges of network's supply temperature
$T'_{min/max}$	feasible ranges of network's return temperature
$b_f^{\max}$	maximum availability of fuel type *f*
Tax_{max}	maximum value for environmental taxes
$\mathbf{Y}_s$	binary decision variable for selection of conversion technologies, networks and resources
$\mathbf{U}_s$	continuous variables for sizing conversion technologies
$\mathbf{B}_f$	continuous variables for resource availability
$\mathrm{t}_{\mathbf{CO_2}}$	continuous variable for CO_2 taxes
$\mathbf{T}_{in/out}^{h/c}$	continuous variables for supply and return temperatures of heating/cooling networks
$\mathbf{M_{CO_2}}$	total environmental impacts in terms of CO_2 emissions
TAC	total annual costs
EFF	overall system's efficiency
Y_s	type of conversion technologies
U_s	size of conversion technologies
$\dot{\mathbf{Q}}_{g,L_h,s_{j/i},p}^{+/-}$	thermo dynamic attributes (heat) of subsystem *s*
$\mathbf{t}_{s,p}^{in/out}$	thermo dynamic attributes (temperature) of subsystem *s*
$\dot{\mathbf{I}}_{s,p}$	subsystem's emissions
$\dot{\mathbf{E}}_{g,L_b,s_e,p}^{+/-}$	subsystem's power
$\dot{\mathbf{M}}_{g,L_b,s_f,p}^{+/-}$	inlet sources and outlet products
$\mathbf{U}_s^{\min/\max}$	feasible ranges of subsystem's utilization
$\mathbf{C}_s$	linear operating expenses
$\mathbf{CI}_s$	investment cost
$C\dot{O}V1/2_{s,p}$	linear terms of hourly operating costs
$COF1/2_s$	linear terms of yearly maintenance costs
Δp	duration of time step *p*
t_{CO_2}	emissions taxes
$U_s^{\min}$	part load power of subsystem *s*
$U_s^{\max}$	max power of subsystem *s*
$\dot{\mathbf{Q}}_{g,L_h,s_i,k,p}^{-}$	the reference heat requirement of cold stream *i*
$\dot{\mathbf{Q}}_{g,L_h,s_j,k,p}^{+}$	the reference heat available of hot stream *j*
$\dot{E}_{g,L_{bl}/L_{bg},s_e,p}^{-/+}$	the reference electricity consumption/production of subsystem *s*
$\dot{M}_{g,L_{bl}/L_{bg},s_f,p}^{-/+}$	the reference resource consumption/production of type *f*
$B_{g,L_{bl}/L_{bg},f,p}$	maximum resource availability of type *f*
m_I^{grid}	the environmental impacts of electricity import from the grid
$m_{f,I}$	the environmental impacts of fuel *f*
$\dot{I}_{s,p}$	the overall emissions of subsystem *s*
$\dot{\mathbf{Q}}_{g,L_h,s'_i,k',p}^{-}$	the reference heat discharging
$\dot{\mathbf{Q}}_{g,L_h,s'_j,k',p}^{+}$	the reference heat charging
$V_{s'}^{\max}$	the maximum feasible volume of storage *s′*
ρ	the density of the considered storage fluid
Cp	the specific heat capacity
$\mathbf{y}_{s,p}$	binary variables for activating subsystem *s* at time *p*
$\mathbf{u}_{s,p}$	continuous variable for utilization level of subsystem *s* at time *p*
$\mathbf{u}_s$	maximum utilization level of subsystem *s*
$\dot{\mathbf{R}}_{g,L_h,k,p}$	the residual heat from the temperature interval *k*
$\dot{\mathbf{E}}_{grid,L_{bg},p}^{+/-}$	the electricity export/import from the grid
$\dot{\mathbf{F}}_{g,L_{bl},f,p}$	the import fuel of type *f* in local layer
$\dot{\mathbf{F}}_{L_{bg},f,p}$	the import fuel of type *f* in global layer
$\dot{\mathbf{I}}_p$	the total emissions at time *p*
$\dot{\mathbf{I}}_{grid,p}$	the emissions of import/export electricity from the grid
$\dot{\mathbf{I}}_{f,p}$	the emissions of import fuel *f*
$\mathbf{u}'_{s',k',j,p}$	continuous variable for the charging rate of storage *s′*
$\mathbf{u}'_{s',k',i,p}$	continuous variable for the discharging rate of storage *s′*
$\mathbf{V^0}_{s',t_{k'}}$	the initial volume of each level $t_{k'}$ of storage *s′*
$\mathbf{V}_{s',t_{k'},p}$	the volume [m^3] of each level during time step *p* of storage *s′*
$\mathbf{V}_{s'}$	the total volume [m^3] of each storage tank *s′*
$\mathbf{y}_{s',p}$	a binary variable for activating the storage subsystem *s′* in time *p*
$\mathbf{y}_{s'}$	a continuous variable which denotes the existence of storage *s′*
$\mathbf{COP}_{s'}$	the total operating cost of storage *s′*
$\mathbf{CI}_{s'}$	the total investment cost of storage *s′*
$\mathbf{I}_{s'}$	the environmental impacts of storage *s′*
$N_{g,g'}$	pipeline from location *g* to *g′*
$g_{x/y}$	geographical coordinates of each location
$\dot{Q}_{N_{g,g'},L_h,k'',p}^{+/-}$	the reference heat transfer of pipeline $N_{g,g'}$
$\dot{\mathbf{Q}}_{N_{g,g'},L_h,k'',p}^{loss}$	the heat loss of pipeline $N_{g,g'}$
$\dot{\mathbf{Q}}_{N_{g,g'},L_h,k''}^{loss,0}$	the linear term of heat loss of pipeline $N_{g,g'}$
$f_{L_h,k''}^{loss}$	the heat loss factor
f_{0,L_h}^{loss}	the reference heat loss factor
T_{gnd}	the ground temperature
ν	the nominal velocity of fluid
ρ	the density of the fluid in the pipeline
Cp	the specific heat capacity
$dl_{N_{g,g'}}$	the length of the pipeline $N_{g,g'}$
$IN_{N_{g,g'}}$	the environmental impacts of pipeline $N_{g,g'}$
$COFN1_{L_h}$	linear terms of network operating cost
$COFN2_{L_h}$	linear terms of network operating cost
$CIN1_{L_h}$	linear terms of network investment cost
$CIN2_{L_h}$	linear terms of network investment cost
$U_{N_{g,g'},L_h}^{\min/\max}$	the minimum and the maximum feasible utilization level of pipeline
$\dot{E}1/2_{N_{g,g'},L'_{bg}}$	the linear terms of the reference pumping power through the network's pipeline
$\dot{\mathbf{Q}}_{N_g,L_h,k'',p}^{+}$	the available heat comes from other locations to location $g \in G$
$\dot{\mathbf{Q}}_{N_g,L_h,k'',p}^{-}$	the residual heat which transfers from location $g \in G$
$\mathbf{u}_{N_{g,g'},L_h,p}$	the utilization level of each pipeline $N_{g,g'}$ in time *p*
$\mathbf{u}_{N_{g,g'},L_h}$	the maximum utilization level of each pipeline $N_{g,g'}$
$\mathbf{d}_{N_{g,g'},L_h}$	the diameter of pipeline $N_{g,g'}$
$\mathbf{COFN}_{L_h}$	the total fixed operating costs of the network
COVN	the total variable operating costs of the network
$\mathbf{CIN}_{L_h}$	the total investment cost of network
$\mathbf{IN}_{L_h}$	the environmental impacts of network