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# Optimal scheduling of heating and power hubs under economic and environment issues in the presence of peak load management



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## ARTICLE INFO

## ABSTRACT

Keywords: Hub energy system Multi-objective model Emission e-constraint approach Max-min fuzzy satisfying method Demand response program Financial issues have been always one of major priorities in scheduling of energy systems. Although these systems are able to serve several types of energy demands but generated emission by these systems is a challenging problem. Since improvement of each one of mentioned issues has negative effects on the other issue therefore a trade-off solution is necessary to be obtained between these issues. In this paper, a multi-objective model has been presented to satisfy both economic and environmental objectives of a hub energy system in the presence of demand response program. In the proposed paper,  $\varepsilon$ -constraint and max-min fuzzy satisfying methods have been employed to solve and select the trade-off solution. The main reason of implementation of demand response program is to reduce operation cost and improve environmental performance of hub energy system. In fact, demand response program transfers some percentage of load from peak periods to off-peak periods to flatten load curve which leads to reduction of cost and emission. A mixed-integer linear programming has been used to simulate the proposed model and general algebraic modeling system software has been utilized to solve it. A sample hub energy system containing renewable and non-renewable energy resources has been studied and comparison results are presented to validate efficiency of proposed techniques.

### 1. Introduction

Recently, optimal operation of energy systems capable of supplying different energy demands called multi-carrier energy systems or hub energy systems has been one of major topics in the scheduling of power systems [1]. Various energy resources like combined heat and power systems (CHP) can be employed to enhance efficiency of operating systems [2]. Moreover, heat energy resources like boiler can be exploited to supply thermal demand [3]. In addition to mentioned non-renewable energy resources, renewable generation units can be integrated in hub energy systems to meet several types of loads [4]. It should be noted that utilization of resources burning fossil fuels in hub energy systems has made emission problem of these systems a big challenge for system operators [5].

Operation of hub energy systems with different purposes and applications has been studied within various researches which are summarized in the following: Economic dispatch problem of multiple energy hub system has been investigated through Self-Adoptive Learning with Time Varying Acceleration Coefficient-Gravitational Search Algorithm in [6]. With the aim of gaining maximum profit, hub energy system has been optimally designed in [7]. Influence of optimizing transmission networks on performance of hub energy system has been

evaluated in [8]. Using a new approach, optimal power flow problem of hub energy systems has been investigated and the results have been compared with the ones obtained through other approaches in [9]. New formulations have been presented for accurate modeling of hub energy system with taking technical constraints into account in [10]. In order to improve performance of a residential hub energy system in the smart grid, a real-time based model has been presented in [11]. Employing controlling structure called hierarchical control structure, economic operation of a multi-carrier energy system has been evaluated in [12]. Optimal performance of multi-carrier energy system and optimal sizing of resources in this system have been investigated in [13]. Economic performance of multi-carrier energy system subject to uncertain behavior of renewable sources has been studied in [14]. Using evolutionary algorithm in [15], optimal operation of multi-carrier energy system has been investigated. Optimal operation of an on-grid multi-carrier energy system including different types of renewable energy sources has been evaluated in [16]. Using Monte Carlo simulation technique in [17], economic performance of hub energy system has been investigated. Optimal operation of hub energy system has been studied through two types of pricing namely dynamic pricing and time-of-use pricing in [18]. Using dispatch strategy, performance of hub energy system subject to curtailment in grid integration and real time pricing has been

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|---|-----------------------------------|--|--------------------------|
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| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | $\eta^B_{gh}$                     | gas to heat efficiency of boiler                                   | $\lambda^{g}$            |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | $\eta_{ee}^{CON}$                 | converter efficiency   | $\lambda^{wa}$           |
| $ \begin{array}{llllllllllllllllllllllllllllllllllll$   | $\eta^e_{ch}$                     | electrical storage charging efficiency                             | $\lambda_s^e$            |
| $ \begin{array}{llllllllllllllllllllllllllllllllllll$   | $\eta^e_{dis}$                    | electrical storage discharging efficiency                          | $\lambda_s^n$            |
| $ \begin{array}{llllllllllllllllllllllllllllllllllll$   | $\eta^h_{ch}$                     | heat storage charging efficiency                                   | $\lambda^{BR}$           |
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| $ \begin{array}{llllllllllllllllllllllllllllllllllll$   |                                   | storage  | $C_t^{st,h}$             |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | $\alpha_{loss}^{e}$               | coefficient for loss of power modeling in electrical storage       | $C_t$<br>Em              |
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| $\begin{array}{cccc} rage & & & & & & & & & & & & & & & & & & &$  | $\alpha_{\max}^n$                 | coefficient for maximum capacity modeling of heat sto-             | $g_{t}^{B}$              |
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| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | $\alpha_{loss}$<br>$\Delta^{NET}$ | unstream network availability                                      | L <sup>ch,e</sup>        |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | ACHP                              | CHP availability   | -1                       |
| $\begin{array}{cccc} & rel = rel (rel or relation of the $  | A <sup>WIND</sup>                 | wind turbine availability  | $I_t^{dis,e}$            |
| $\begin{array}{c} C_{e}^{st,h} & \text{nominal capacity of heat storage} & I_{t}^{eh,h} & I_{t}^$  | $C_{a}^{st,e}$                    | nominal capacity of electrical storage                             | -                        |
| $\begin{array}{lll} & EF_{CO}^{LPP} & CO_2 \mbox{ emission factor for CHP unit} & I_t^{dis,h} \\ & EF_{CO}^{CHP} & SO_2 \mbox{ emission factor for CHP unit} & I_t^{dis,h} \\ & EF_{NO}^{CHP} & NO_2 \mbox{ emission factor for CHP unit} & I_t^{shup,e} \\ & EF_{NO}^{B} & CO_2 \mbox{ emission factor for boiler} & I_t^{shup,e} \\ & EF_{NO}^{B} & NO_2 \mbox{ emission factor for boiler} & I_t^{shup,e} \\ & EF_{NO}^{B} & NO_2 \mbox{ emission factor for gas consumption in residential} \\ & section & P_t^{ch,e}, I \\ & section & P_t^{los,h} \\ & section & P_t^{los,h} \\ & section & P_t^{los,h} \\ & section & P_t^{los,h}, I \\ & sec$   | $C_c^{st,h}$                      | nominal capacity of heat storage                                   | $I_t^{ch,h}$             |
| $\begin{array}{cccc} EF_{SO}^{CIP} & SO_2 \text{ emission factor for CHP unit} & I_t^{dis,h} \\ EF_{SO}^{CIP} & NO_2 \text{ emission factor for CHP unit} \\ EF_{CO}^{RP} & CO_2 \text{ emission factor for boiler} & I_t^{shup,e} \\ EF_{SO}^{B} & SO_2 \text{ emission factor for boiler} & I_t^{shdo,e} \\ EF_{NO}^{B} & NO_2 \text{ emission factor for gas consumption in residential} \\ & \text{section} & P_t^{eh,e} \\ EF_{SO}^{L} & SO_2 \text{ emission factor for gas consumption in residential} \\ & \text{section} & P_t^{eh,h} \\ EF_{CO}^{N} & NO_2 \text{ emission factor for gas consumption in residential} \\ & \text{section} & P_t^{eh,h} \\ EF_{NO}^{N} & NO_2 \text{ emission factor for gas consumption in residential} \\ & \text{section} & P_t^{eh,h} \\ EF_{CO}^{Net} & CO_2 \text{ emission factor for gas consumption in residential} \\ & \text{section} & P_t^{eh,h} \\ EF_{CO}^{Net} & SO_2 \text{ emission factor for upstream network power} & P_t^{el,DRI} \\ & \text{section} & P_t^{el,DRI} \\ & \text{section} & \text{section} & P_t^{eh,h} \\ & P_t^{eh,h} \\ & \text{section} & P_t^{eh,h} \\ & P_t^{eh,h} \\ & \text{section} & P_t^{eh,h} \\ $   | $EF_{CO}^{CHP}$                   | $CO_2$ emission factor for CHP unit                                |                          |
| $\begin{array}{lll} EF_{NO}^{LIP} & \text{NO}_2 \text{ emission factor for CHP unit} & I_t^{shup,e} \\ EF_{CO}^B & \text{CO}_2 \text{ emission factor for boiler} & I_t^{shup,e} \\ EF_{SO}^B & \text{SO}_2 \text{ emission factor for boiler} & I_t^{shup,e} \\ EF_{NO}^B & \text{NO}_2 \text{ emission factor for boiler} & I_t^{shup,e} \\ EF_{NO}^B & \text{NO}_2 \text{ emission factor for gas consumption in residential} \\ & \text{section} & P_t^{ch,e}, \\ & \text{section} & P_t^{ch,h}, \\ & P_t^{ch,h}, \\ & \text{section} & P_t^{ch,h}, \\ & P_t^{ch,h}, \\ & P_t^{ch,h}, \\ & P_t^{ch,h}, \\ & \text{section} & P_t^{ch,h}, \\ & $   | $EF_{SO}^{CHP}$                   | $SO_2$ emission factor for CHP unit                                | $I_t^{dis,h}$            |
| $\begin{array}{lll} EF_{CO}^{B} & \mathrm{CO}_2 \mbox{ emission factor for boiler} & I_t^{mhple} \\ EF_{SO}^{B} & \mathrm{SO}_2 \mbox{ emission factor for boiler} & I_t^{shdo,e} \\ EF_{NO}^{B} & \mathrm{NO}_2 \mbox{ emission factor for gas consumption in residential} & section & P_t^{ch,e}, I_t \\ section & I_t^{shdo,e} & P_t^{ch,e}, I_t \\ section & I_t^{ch,e}, I_t \\ setimary & I_t^$   | $EF_{NO}^{CHP}$                   | NO <sub>2</sub> emission factor for CHP unit                       | shup a                   |
| $\begin{array}{lll} EF_{SO}^{B} & \mathrm{SO}_{2} \text{ emission factor for boiler} & I_{t}^{shdo,e} \\ EF_{NO}^{B} & \mathrm{NO}_{2} \text{ emission factor for boiler} & I_{t}^{shdo,e} \\ EF_{CO}^{L} & \mathrm{CO}_{2} \text{ emission factor for gas consumption in residential} & section & P_{t}^{ch,e}, I_{t}^{shdo,e} \\ EF_{SO}^{L} & \mathrm{SO}_{2} \text{ emission factor for gas consumption in residential} & section & P_{t}^{ch,e}, I_{t}^{shdo,e} \\ EF_{NO}^{L} & \mathrm{NO}_{2} \text{ emission factor for gas consumption in residential} & section & P_{t}^{ch,e}, I_{t}^{shdo,e} \\ exction & EF_{CO}^{L} & \mathrm{CO}_{2} \text{ emission factor for gas consumption in residential} & section & P_{t}^{ch,e}, I_{t}^{shdo,e} \\ EF_{CO}^{Net} & \mathrm{SO}_{2} \text{ emission factor for upstream network power} & P_{t}^{el,DRI} \\ EF_{SO}^{Net} & \mathrm{SO}_{2} \text{ emission factor for upstream network power} & P_{t}^{shdo,e} \\ eF_{NO}^{Net} & \mathrm{SO}_{2} \text{ emission factor for upstream network power} & P_{t}^{shdo,e} \\ g_{min}^{net} & \text{gas network minimum capacity} & P_{t}^{shdo,e} \\ g_{max}^{net} & \text{gas demand in residential section} & wa_{t}^{net} \\ LPF_{shdo,e}^{shdo,e} & \text{coefficient for increased electrical load} & Abbree \\ P_{min}^{e} & upstream network maximum capacity & DRP \\ g_{max}^{e} & upstream network maximum capacity & DRP \\ g_{max}^{e} & nominal capacity of CHP & MILP \\ p_{e}^{CHP} & nominal capacity of CHP & MILP \\ p_{e}^{R} & nominal capacity of CHP & MILP \\ p_{e}^{R} & nominal capacity of CHP & TOU \\ p_{r} & wind turbine rated power \end{array}$   | $EF_{CO}^B$                       | CO <sub>2</sub> emission factor for boiler                         | $I_t^{snup,c}$           |
| $ \begin{array}{lll} EF_{NO}^{hO} & \mathrm{NO}_{2} \mbox{ emission factor for boiler} & I_{t} $  | $EF_{SO}^B$                       | SO <sub>2</sub> emission factor for boiler                         | <b>⊤</b> shdo.e          |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | $EF_{NO}^{B}$                     | NO <sub>2</sub> emission factor for boiler                         | $I_t^{max}$              |
| section $P_t$ $EF_{SO}^L$ SO2 emission factor for gas consumption in residential<br>section $p_t^{ch, p}$ $EF_{NO}^L$ NO2 emission factor for gas consumption in residential<br>section $p_t^{loss, e}$ $EF_{NO}^{LO}$ CO2 emission factor for upstream network power $P_t^{losl, p}$ $EF_{SO}^{Net}$ SO2 emission factor for upstream network power $P_t^{losl, p}$ $EF_{NO}^{Net}$ NO2 emission factor for upstream network power $P_t^{shup, e}$ $EF_{NO}^{Net}$ NO2 emission factor for upstream network power $P_t^{shup, e}$ $EF_{NO}^{Net}$ NO2 emission factor for upstream network power $P_t^{shup, e}$ $EF_{NO}^{Net}$ gas network minimum capacity $P_t^{wi}$ $g_{max}^{net}$ gas demand in residential section $wa_t^{net}$ $LPF^{shup, e}$ coefficient for increased electrical loadAbbree $LPF^{shdo, e}$ upstream network maximum capacityCHP $P_{max}^{e}$ upstream network maximum capacityDRP $p_c^{CHP}$ nominal capacity of CHPMILP $p_c^{CHP}$ nominal capacity of CHPMILP $p_r$ wind turbine rated powerTOU  | $EF_{CO}^{L}$                     | $CO_2$ emission factor for gas consumption in residential          | n <sup>e</sup>           |
| $\begin{array}{cccccccccccccccccccccccccccccccccccc$  | $EE^L$                            | section  | $P_t$<br>$n^{ch,e}$      |
| $ \begin{array}{llllllllllllllllllllllllllllllllllll$   | Erso                              | SO <sub>2</sub> emission factor for gas consumption in residential | $P_t \rightarrow P_t$    |
| $\begin{array}{cccccccccccccccccccccccccccccccccccc$  | $EF_{VO}^{L}$                     | $NO_2$ emission factor for gas consumption in residential          | $P_t$ , $P_t$            |
| $EF_{CO}^{Net}$ $CO_2$ emission factor for upstream network power $p_t^{el.DR1}$ $EF_{CO}^{Net}$ $SO_2$ emission factor for upstream network power $p_t^{el.DR1}$ $EF_{Not}^{Net}$ $NO_2$ emission factor for upstream network power $p_t^{shup,e}$ $EF_{Not}^{Net}$ $NO_2$ emission factor for upstream network power $p_t^{shup,e}$ $g_{max}^{net}$ gas network minimum capacity $p_t^{wi}$ $g_{max}^{ret}$ gas network maximum capacity $p_t^{wi}$ $e_t^{r}$ gas demand in residential section $wa_t^{net}$ $LPF^{shdo,e}$ coefficient for increased electrical loadAbbre $e_{min}^{e}$ upstream network minimum capacityCHP $p_m^{e}$ upstream network maximum capacityDRP $p_c^{T}$ transformer rated capacityDRP $p_c^{CHP}$ nominal capacity of CHPMILP $p_c^{R}$ nominal capacity of CHPTOU $p_r$ wind turbine rated powerTOU   | LI NO                             | section  | $P_t$                    |
| $\begin{array}{lll} EF_{SO}^{Net} & SO_2 \text{ emission factor for upstream network power} & P_t \\ F_{SO}^{Net} & NO_2 \text{ emission factor for upstream network power} & P_t^{shup,e} \\ g_{min}^{net} & gas network minimum capacity & P_t^{wi} \\ g_m^{net} & gas network maximum capacity & P_t^{wi} \\ g_t^{l} & gas demand in residential section & wa_t^{net} \\ LPF^{shdo,e} & coefficient for increased electrical load & Abbre \\ e_{min}^{e} & upstream network minimum capacity & CHP \\ p_m^{e} & upstream network maximum capacity & DRP \\ g_c^{T} & transformer rated capacity & DRP \\ g_c^{CHP} & nominal capacity of CHP & MILP \\ p_r^{B} & nominal capacity of CHP & TOU \\ p_r & wind turbine rated power & TOU \\ \end{array}$   | $EF_{CO}^{Net}$                   | $CO_2$ emission factor for upstream network power                  | P <sub>t</sub>           |
| $\begin{array}{lll} EF_{NO}^{Net} & \mathrm{NO}_2 \text{ emission factor for upstream network power} & p_t^{Net} \\ g_{min}^{net} & \mathrm{gas network minimum capacity} & p_t^{wi} \\ g_{max}^{net} & \mathrm{gas network maximum capacity} & p_t^{wi} \\ g_t^{l} & \mathrm{gas demand in residential section} & wa_t^{net} \\ LPF^{shdo,e} & \mathrm{coefficient for increased electrical load} & LPF^{shdo,e} \\ coefficient for decreased electrical load & Abbre \\ p_{min}^{e} & \mathrm{upstream network minimum capacity} & CHP \\ p_{max}^{e} & \mathrm{upstream network maximum capacity} & DRP \\ p_c^{T} & \mathrm{transformer rated capacity} & DRP \\ p_c^{CHP} & \mathrm{nominal capacity of CHP} & MILP \\ p_r^{B} & \mathrm{nominal capacity of CHP} & TOU \\ p_r & \mathrm{wind turbine rated power} & TOU \end{array}$  | $EF_{SO}^{Net}$                   | SO <sub>2</sub> emission factor for upstream network power         | P <sub>t</sub>           |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | $EF_{NO}^{Net}$                   | NO <sub>2</sub> emission factor for upstream network power         | $P_t$                    |
| $\begin{array}{ll} g_{max}^{net} & \text{gas network maximum capacity} & p_t^{net} \\ g_{max}^{l} & \text{gas demand in residential section} & wa_t^{net} \\ p_t^{l} & \text{gas demand in residential section} & wa_t^{net} \\ LPF^{shup,e} & \text{coefficient for increased electrical load} & \\ LPF^{shdo,e} & \text{coefficient for decreased electrical load} & \\ p_{max}^{e} & \text{upstream network minimum capacity} & \\ p_{max}^{e} & \text{upstream network maximum capacity} & \\ p_c^{T} & \text{transformer rated capacity} & \\ p_c^{CHP} & \text{nominal capacity of CHP} & \\ p_c^{B} & \text{nominal capacity of CHP} & \\ p_r & \text{wind turbine rated power} & \\ \end{array}$  | $g_{\min}^{net}$                  | gas network minimum capacity                                       | $P_t^{wi}$               |
| $\begin{array}{cccc} g_t^l & \mbox{gas} \mbox{ demand in residential section} & \mbox{wa}_t^{IIII} & \mbox{wa}_t^{IIIII} & \mbox{coefficient for increased electrical load} & \mbox{LPF}^{shup,e} & \mbox{coefficient for decreased electrical load} & \mbox{Abbre} & \mbox{p}_{min}^{IIIIII} & \mbox{upstream network minimum capacity} & \mbox{CHP} & \mbox{maximum capacity} & \mbox{CHP} & \mbox{maximum capacity} & \mbox{DRP} & \mbox{gas}_t^{IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII$   | $g_{\max}^{net}$                  | gas network maximum capacity                                       | $p_t^{m}$                |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | $g_t^l$                           | gas demand in residential section                                  | $wa_t$                   |
| LPFcoefficient for decreased electrical loadHouse $p_{min}^e$ upstream network minimum capacityCHP $p_{max}^T$ upstream network maximum capacityDRP $p_c^T$ transformer rated capacityDRP $p_c^{CHP}$ nominal capacity of CHPGAMS $p_c^B$ nominal capacity of CHPMILP $p_r$ wind turbine rated powerTOU   | LPF <sup>shup,e</sup>             | coefficient for increased electrical load                          | Abbra                    |
| $\begin{array}{llllllllllllllllllllllllllllllllllll$  | LPF <sup>shdo,e</sup>             | coefficient for decreased electrical load                          | AUUre                    |
| $p_{max}^{*}$ upstream network maximum capacityCHP $p_{c}^{T}$ transformer rated capacityDRP $p_{c}^{CHP}$ nominal capacity of CHPGAMS $p_{c}^{B}$ nominal capacity of CHPMILP $p_{r}^{B}$ wind turbine rated powerTOU  | $p_{\min}^e$                      | upstream network minimum capacity                                  | СНР                      |
| $p_c'$ transformer rated capacityDR $p_c^{CHP}$ nominal capacity of CHPGAMS $p_c^B$ nominal capacity of CHPMILP $p_r$ wind turbine rated powerTOU   | $p_{\max}^{c}$                    | upstream network maximum capacity                                  | DRP                      |
| $p_c^{chn}$ nominal capacity of CHPMILP $p_c^B$ nominal capacity of CHPMILP $p_r^B$ wind turbine rated powerTOU   | $p_c^{\prime}$                    | transformer rated capacity   | GAM                      |
| $p_c^{"}$ nominal capacity of CHP TOU $p_r$ wind turbine rated power  | $P_{c_{R}}^{C_{R}}$               | nominal capacity of CHP  | MILP                     |
| $p_r$ wind turbine rated power  | $p_c^{B}$                         | nominal capacity of CHP  | TOU                      |
|   | <i>P</i> <sub>r</sub>             | wind turbine rated power   |                          |

investigated in [19]. Considering uncertainty modeling of wind, price and load, optimal operation of hub energy system has been investigated in [20]. Using a heuristic technique called Time Varying Acceleration Coefficient Gravitational Search algorithm, optimal performance of hub energy system has been evaluated in [21]. With the aim of minimizing total cost, optimal operation of hub energy system considering uncertainty of renewable sources has been studied using stochastic

| $p_t^{el}$            | electrical load                                      |
|-----------------------|--|
| $p_t^h$               | heating load   |
| $wa_t^l$              | water demand   |
| $wa_{\min}$           | minimum limitation of water network                  |
| wa <sub>max</sub>     | maximum limitation of water network                  |
| $w_{co}, w_{ci}, w_r$ | cut-out, cut-in and rated speeds of wind turbine     |
| w(t)                  | wind speed   |
| x, y, z               | coefficients for modeling generation of wind turbine |
| $\lambda_t^{e}$       | price of purchased power from upstream network       |
| $\lambda^{wi}$        | generation cost of wind turbine                      |
| $\lambda^{g}$         | gas price  |
| $\lambda^{wa}$        | water price  |
| $\lambda_s^e$         | operation cost of electrical storage                 |
| $\lambda_s^h$         | operation cost of heat storage                       |
| $\lambda^{DR}$        | cost of demand response                              |
|                       |  |
| Variables             |  |

#### total operation cost of hub energy system available energy of electrical storage available energy of heat storage total emission generated in hub energy system IP gas consumption of CHP gas consumption of boiler total purchased gas from gas network binary variable, 1 if electrical storage is in charging mode; otherwise 0 binary variable, 1 if electrical storage is in discharging mode; otherwise 0 binary variable, 1 if heat storage is in charging mode; otherwise 0 binary variable, 1 if heat storage is in discharging mode; otherwise 0 p.e binary variable, 1 if electrical load is increased; otherwise o.e binary variable, 1 if electrical load is decreased; otherwise purchased power form upstream network <sup>e</sup>,p<sup>,dis,e</sup> charge/discharge power of electrical storage $^{h}, p_{t}^{dis,h}$ charge/discharge heat of thermal storage s,e loss of power in electrical storage s.h loss of heat in heat storage DRP electrical load in the presence of DRP ıp,e increased electrical load lo,e decreased electrical load produced power by wind turbine net purchased water from water network previations D combined heat and power system п demand response program MS general algebraic modeling system mixed-integer linear programming

programming in [22]. A paradigm has been presented to optimize operation of interconnected multi-carrier energy systems in [23]. Employing teaching–learning based optimization algorithm, energy flow problem of multi-carrier energy system has been evaluated in [24]. Optimal dispatch strategies and coordinated operation of a hub energy system have been investigated in [25]. Using multi-agent systems approach, optimal operation of hub energy system has been evaluated

time-of-use rates of demand response program

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