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Cost-efficient multi-energy management with flexible complementarity strategy for energy internet

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HIGHLIGHTS

- A multi-energy management method with energy complementarity prosumers was proposed.
- A multi-objective optimisation framework was developed to reduce total energy cost.
- The economic impact of the energy complementarity strategy was investigated.
- The new method could promote the sustainable development of the urban energy system.

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ABSTRACT

The increasing complexities of energy internet integrated with distributed renewable energy resources and multiple energy infrastructures require more effective multi-energy management method. The prosumers with multiparty interaction represent major potential contributors for comprehensively improving the energy efficiency and socioeconomic benefits. In this paper, a novel multi-energy management strategy based on the complementarity of multi-energy demand was proposed to explore optimal energy scheduling problems of prosumers. The residential prosumer with a multi-energy coupling matrix and the industrial prosumer with a resource-task network were formulated to optimise the local operations. Furthermore, a joint planning for the prosumers was developed to minimise the global operating costs, where the prosumers' interests in terms of the energy exchange process were formulated as a multi-objective optimisation problem based on the Pareto efficiency theory. In addition, an optimisation method that integrates the epsilon-constraint algorithm and the extreme points of the feasible solution space was proposed to obtain better and more diverse solutions. The proposed methodology was applied to an urban multi-energy system. Simulation results demonstrated that the proposed multi-energy management method could effectively solve the optimal energy scheduling problems. At the compromise solution point, cost reductions of 7% and 10% can be obtained by the two prosumers on a summer day, with cost reductions of 9% and 11% obtained on a winter day. The use of multi-energy management method could establish a win-win relationship for prosumers and generate substantial benefits for the whole system.

1. Introduction

The rapid growth of the energy demand and limited resources have led to serious global concerns about the depletion of energy resources [1]. Related research has indicated that fossil fuel combustion for energy production is a major contributor to air pollution and the greenhouse effect [2]. The literature [3] also shows that a particularly large fraction (35–36%) was from fuel combustion in power plants. The problems call for collaborative and multidisciplinary research on energy sustainability [4,5]. As a promising next-generation power system, the smart grid (SG) has been presented, which involves the construction of an intelligent power delivery system by enabling bidirectional flows of electricity and information [6]. However, in practice, an energy system contains a variety of complex multi-energy carriers, and energy can be generated, converted, transmitted, and consumed in flexible ways. Moreover, the SG still has limited flexibility for distributed supply and demand because of its reliance on the traditional grid infrastructure.

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Nomenclature

Abbreviations

EI	energy internet
SG	smart grid
EC	energy complementarity
DR	demand respond
LF	ladle furnace
CC	continuous caster
MEM	multi-energy management
WHR	waste heat recovery
RTN	resource-task network
TOU	time-of-use
ESS	energy storage system
EAF	electric arc furnace
AOD	argon oxygen decarburisation
CCHP	combined cooling, heating, and power

Set

i	index for device participants in MEM
j	index for tasks in RTN
l	index for energy loads
m	index for the intermediate products
t/θ	index for time (uniform/relative)
$e/h/c/g$	index for energy carriers (electricity/heat/cooling/gas)
E	index for the storage forms
EL	index for the electricity resource in RTN
EC	index for the energy forms in EC
WH	index for the waste heat resource
EAF/WHR	index for the equipment resources in RTN

Parameters

n	the energy conversion factors
δ	duration (minutes) of every time slot
$\alpha^{loss}_{i_E}$	standby energy loss of the i_Eth storage
$\eta^{ch}_{i_E}$	the charge efficiency of the i_Eth storage
$\eta^{dis}_{i_E}$	the discharge efficiency of the i_Eth storage
$ESS^{\min}_{i_E}$	the minimum capacity of the i_Eth storage
$ESS^{\max}_{i_E}$	the maximum capacity of the i_Eth storage
$ESS^{r}_{i_E}$	the rated capacity of the i_Eth storage
$U_{i_{CCHP}}$	the upward ramp rate of the CCHP units
$D_{i_{CCHP}}$	the downward ramp rate of the CCHP units
$P^{r}_{i_{CCHP}}$	the rated capacity of the CCHP units
$price_{e,t}$	the TOU price of electricity
$price_{h,t}$	the TOU price of heat
$price_{g,t}$	the TOU price of natural gas

Binary variables

$N^{ch}_{i_E,t}$	charging status of the i_Eth storage at time t (equal to 1 if i_Eth storage is charged at time t and 0 otherwise)
$N^{dis}_{i_E,t}$	discharging status of the i_Eth storage at time t (equal to 1 if i_Eth storage is discharged at time t and 0 otherwise)
$N_{j,t-\theta}$	interaction status of the jth task in RTN at time $t-\theta$ (equal to 1 if θ is earlier than t and 0 otherwise)
$N_{j_{EAF},t}$	occupation status of resource *EAF* in the jth task at time t (equal to 1 if *EAF* is occupied at time t and 0 otherwise)
$N_{j_{AOD},t}$	occupation status of resource *AOD* in the jth task at time t (equal to 1 if *AOD* is occupied at time t and 0 otherwise)
$N_{j_{LF},t}$	occupation status of resource *LF* in the jth task at time t (equal to 1 if *LF* is occupied at time t and 0 otherwise)
$N_{j_{WHR},t}$	occupation status of resource *WHR* in the jth task at time t (equal to 1 if *WHR* is occupied at time t and 0 otherwise)
$N_{j_{EAF_m},t}$	transfer status of intermediate product EAF_m in the jth task at time t (equal to 1 if EAF_m is transferred at time t and 0 otherwise)
$N_{j_{AOD_m},t}$	transfer status of intermediate product AOD_m in the jth task at time t (equal to 1 if AOD_m is transferred at time t and 0 otherwise)
$N_{j_{LF_m},t}$	transfer status of intermediate product LF_m in the jth task at time t (equal to 1 if LF_m is transferred at time t and 0 otherwise)
$N_{j_{WH_m},t}$	transfer status of intermediate product WH_m in the jth task at time t (equal to 1 if WH_m is transferred at time t and 0 otherwise)

Variables

v	the energy distribution factors at time t
ρ	the coupling factors among ESS at time t
π_t	the penetration index (ratio of residential loads and CCHP capacity) at time t
$\tau_{i_l,t}\%$	the limits of the i_lth load's predicted deviation at time t
$u_{i_l,t}$	the spinning reserve demand of the i_lth load at time t
$s_{Ie,t}$	the electricity resource for the industrial prosumer at time t
$\mu_{r,j,\theta}$	the quantify of resource r that is occupied or produced by task j at time θ
M	the modification of loads by ESS at time t
R_t	the spinning reserve demand of the sudden increase in load and the forced outage at time t
$E^{ch}_{i_E,t}$	the charging capacity of the i_Eth storage at time t
$E^{dis}_{i_E,t}$	the discharging capacity of the i_Eth storage at time t
$ESS_{i_E,t}$	the remaining capacity of the i_Eth storage at time t
$P_{i_{CCHP},t}$	the theoretical power of the i_{CCHP}th unit at time t
$\Pi_{EL,t}$	the total electricity consumption of the steel plant with self-scheduling at time t
$\Pi_{WH_m,t}$	the total waste heat production of the industrial prosumer with co-scheduling at time t
Z_1	the total energy cost of the residential prosumer with co-scheduling during time slot T
Z_2	the total energy cost of the industrial prosumer with co-scheduling during time slot T

As a feasible solution, the energy internet (EI) [7], was proposed to obtain a highly economical, efficient, flexible, and sustainable future energy system. It integrates multi-energy carriers, including renewable energy, and promotes the deep integration of the energy flow, information flow, and business flow [8]. Compared with the SG, the EI has a wide range of advantages in the following areas. (1) The individualised utilisation, optimal allocation, and targeted management of multiple energy sources are emphasized in the EI [9], while the SG only focuses on the optimal supply of a single form of energy based on consumption. (2) The SG pays more attention to the inheritance and transformation of the traditional power grid, with passive user access and centralised control primarily adopted [10]. In contrast, the EI can support energy plug-and-play during the processes of production, storage, and consumption, with the operational topology no longer limited to a specific structure [11]. In addition, decision-making units have the advantage of flexible distributed control nodes for autonomous energy deployment, which also greatly enhances the security, flexibility, and sustainability of the EI system [12,13]. (3) A wide range of self-energy bodies or micro-power stations become the main body when using the EI, which is bound to spawn a more economical business model [14].