DECENTRALIZED CONTROL FOR COMBINED HEAT AND POWER SYSTEM IN ENERGY COMMUNITY

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ABSTRACT

The combined heat and power systems seeks to maximize the value between heat and electricity. To integrate CHP system into local energy trading whist optimally utilize low carbon resources in the local energy community, the centralized optimization model suffers from challenges in twofold: i) additional communication devices between prosumers, and ii) large scale optimization model that can handle the large volume of controllable components (battery storage, EV, fuel cells) engaged. Therefore, this paper attempts to achieve optimal operation of the CHP system in local energy community. To reduce the computational complexity, this paper proposes a decentralized energy management system to achieve both benefits of individual prosumers as well as the system level targets. Results indicate the proposed system can: i) largely reduce energy cost for prosumers; ii) the proposed method can achieve system level targets, i.e., system peak reduction, in a decentralized way.

INTRODUCTION

With the environmental targets set by the governments worldwide, the main target of modern power system is to decarbonize generation and demand, hence inspires the presence of many renewable techniques. For example, in the UK, the greenhouse gas emission target has been set to be 20% of the current status in the future decades [1]. To achieve this foreseen goal with the minimum investment to the existing power system, it calls for technical innovations to achieve higher energy efficiency with the available low carbon resources in the demand side. One of the key technical innovation is the Combined Heat and Power (CHP) system.

The Combined Heat and Power (CHP) system is literally to maximise the value of heat and power supply and consumption by operate the exchanges between these two types of energy [2]. To the existing literature, the operation of CHP system has been widely investigated to achieve global optimization within the smart buildings, smart homes, or a distribution substation. Most of prior works [3, 4] focuses on the minimisation of the union costs between heat and electricity within the smart buildings/homes. However, from the perspective of local energy community, it is necessary to develop CHP systems that are not only achieves local optimization but also benefit the whole energy community. Therefore, some works investigated how to operate the CHP system in a service region. For instance, work [5, 6] aims to achieve optimal operation of CHP system in the microgrid. In these works, centralised programming models are widely developed to approach the global optimization point of operational solution. Despite the effectiveness, these works somehow bring up additional unsolved challenges: i) on the one hand, it highly relies on the information exchanges between prosumers, hence causes a considerable investment in communication devices in the local energy community; ii) on the other hand, centralised programming model to handle hundreds, thousands of prosumers in the wider energy community may suffer from expensive computational costs and hence create obstacles for real-time operation.

In order to tackle the unsolved challenges in local energy communities, this paper proposes a decentralized operation scheme that can achieve operational targets both for individual prosumers and the whole energy community. Compared to traditional programming model individual prosumers, the proposed method adds a regularization term to the objective function to rectify the curve shape of electricity and gas demand without compromise the local benefits. Consequently, the rectified demand curve of electricity and gas are expected to maximize the value for the operation of energy community, i.e., to achieve low system peak and uncertainty of electricity and gas demand.

To benchmark the proposed method, a classical strategy is deployed as the compared algorithm, which minimize the energy cost of electricity and gas in individual households. The results compare: i) the peak and uncertainty reduction of individual households; ii) and the accumulated system peak and uncertainty of electricity and gas for the whole energy community.

The remainder of this paper is organized as follows. The concept and general model of CHP system is briefly introduced in Section II. The proposed operation scheme for CHP system is then introduced and formulated in Section III. Section IV presents the experiment settings. The results and conclusions are demonstrated afterwards in Section V and VI.

COMBINED HEAT AND POWER SYSTEM

This section briefly introduced the concept and model formulation of the CHP system. It contains system scenario and model formulation.

Scenario of CHP systems

CHP is proposed to raise energy efficiency. It can provide electricity and heat simultaneously and the efficiency can be even up to 85%-90% through energy cascade utilization [2]. Assuming each horse is equipped with an energy storage (ES) and a CHP unit. The energy flow of household CHP system is shown in Fig. 1. ES is charged at low price period and discharge at peak load period to reduce household peak load as well as system peak load. CHP has a high energy conversion efficiency. It supplies household electricity load and heat load to reduce the load uncertainty and increase the demand flexibility.

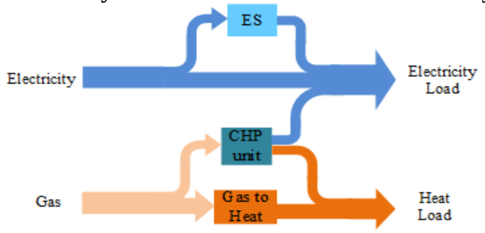

Fig. 1. Energy flow of CHP system

Model formulation of CHP unit

CHP unit can operate in two modes, namely with fixed and variable heat/electricity production rate [3, 7]. The mode with variable heat/electricity production rate has a flexible operational condition and is introduced here. Its feasible operating area is shown in Fig. .

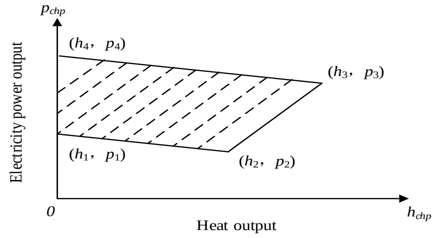

Fig. 2. The feasible operation area of CHP unit

Four vertices of the operation area are defined as (h_k, p_k). Any point in the operation area can be expressed as the convex combination of these four vertices. So, the electricity and heat production of a CHP unit are expressed as:

$$p_{cht,t} = \sum_{k=1}^{4} \alpha_{k,t} p_k \tag{1}$$

$$h_{cht,t} = \sum_{k=1}^{4} \alpha_{k,t} h_k \tag{2}$$

where $p_{cht,t}$ and $h_{cht,t}$ are the electricity and heat output of a CHP unit; $\alpha_{k,t}$ is the combination coefficient, which satisfy the following constraints:

$$0 \le \alpha_{k,t} \le 1 \tag{3}$$

$$\sum_{k=1}^{4} \alpha_{k,t} = b_{chp,t} \tag{4}$$

where $b_{chp,t}$ represents the operating status of the CHP unit.

The gas consumption of a CHP unit is generally expressed as a quadratic function of its electricity and heat output [3]:

$$g_{chp,t} = b_1 + b_2 p_{chp,t} + b_3 p_{chp,t}{}^2 + b_4 h_{chp,t} + b_5 h_{chp,t}{}^2 \tag{5}$$

where b_i $i \in [1,5] \cap \mathbb{Z}$ are constant coefficients.

Model formulation of ESS

In this paper, the controllable resources in the electricity side is an in-home ES that can absorb and discharge electricity. Therefore, the investigated CHP system will utilize the ES as one of the controllable unit for providing flexibility. Traditionally, the ES is deployed in smart buildings/homes to alter the pattern of energy consumption, hence to achieve reduced energy cost and other optimization targets. Assuming the optimization horizon is segmented into M intervals and the time duration of each time interval is denoted as T. In this paper, the interval T is chosen as half-hourly interval. In details, the constraints are:

$$0 \le p_{ch,t} \le b_{ch,t} P_{ch}, \forall t \in [1, M] \cap \mathbb{Z} \tag{6}$$

$$0 \le p_{dch,t} \le b_{dch,t} P_{dch}, \forall t \in [1, M] \cap \mathbb{Z} \tag{7}$$

$$b_{ch,t} + b_{dch,t} \le 1, \forall t \in [1, M] \cap \mathbb{Z} \tag{8}$$

$$b_{ch,t}, b_{dch,t} \in \{0,1\} \tag{9}$$

$$E_{min} \le e_t \le E_{max}, \forall t \in [1, M] \cap \mathbb{Z} \tag{10}$$

$$e_t = e_{t-1} + T(p_{ch,t}\eta_{ch} - \frac{p_{dch,t}}{\eta_{dch}}), \forall t \in [1, M] \cap \mathbb{Z} \tag{11}$$

$$0 \le x_t \le P_h, \forall t \in [1, M] \cap \mathbb{Z} \tag{12}$$

where $p_{ch,t}$ and $p_{dch,t}$ refer to control variables of battery charging and discharging power. Given these constraints of power and energy, the ES can provide flexibility in demand within the limits.

PROPOSED METHODOLOGY

This paper investigates the advanced CHP operation scheme that are not only save the unified energy costs (electricity and gas), but also to reduce system level peak and uncertainty, to bring up benefits to the system operators. This section presents the proposed decentralized operation scheme for CHP system in the energy community. Specifically, the formulation of the programming model for the proposed method are introduced.

Traditional model of CHP system

Objective I: to minimize household energy bills

The first objective for household EMS optimization is to minimize the energy bills for the household customer under given TOU tariffs. Assuming the predicted daily electricity demand is $\{d_{e,t}\}_{t\in[1,48]\cap\mathbb{Z}}$, heat demand is $\{d_{h,t}\}_{t\in[1,48]\cap\mathbb{Z}}$, daily electricity TOU tariffs is $\{C_{e,t}\}_{t\in[1,48]\cap\mathbb{Z}}$, and gas tariff is $\{C_{g,t}\}_{t\in[1,48]\cap\mathbb{Z}}$ .Therefore, this objective can be formulated as the sum of energy cost:

$$(\boldsymbol{P1}) \;\; Objective\ I \coloneqq min \;\; T \sum_{t=1}^{M} C_{e,t} x_t + C_{g,t} g_t \tag{13}$$

Subjected to:

$$x_t = d_{e,t} + p_{ch,t} - p_{dch,t} - p_{chp,t} \tag{14}$$

$$g_t = g_{chp,t} + (d_{h,t} - h_{chp,t})/\eta_h, \forall t \in [1, M] \cap \mathbb{Z} \tag{15}$$

and (1) –(12)

where x_t is the net electricity demand of the household. $d_{e,t}$ refers to the inherent household electric demand. η_h refers to the gas to heat conversion efficiency.

Programming model of proposed CHP system

Objective II: Minimize household energy bills and smooth household demand

To reduce system peak load and uncertainty in a decentralized manner, a L_2-norm term is added to the secondary objective function to regularize the shape of electricity and gas demand curve, hence to smooth the demand curve. Consequently, the proposed model can smooth the accumulated demand at system level. The objective of programming model ($P2$) is formulated as:

$$(\boldsymbol{P2})\ Objective\ II \coloneqq min\ \ T\sum_{t=1}^{M} C_{e,t}x_t + C_{g,t}g_t + \lambda\sum_{t=1}^{M}(x_t-\bar{x})^2 + (g_t-\bar{g})^2 \qquad (16)$$

Subjected to: (1) –(12) and (14) – (15)

where, parameter λ is the weight factor [8] of second objective term compared to first objective term. $\bar{x}$ refers to average net electricity demand in a household. $\bar{g}$ refers to average gas demand in a household.

EXPERIMENT SETTINGS

This section briefly introduces the data description and benchmark to validate the proposed methodology.

Data description

In this paper, the smart metering data deployed in the demonstration are recorded from Irish domestic electricity dataset, which is published by the Smart Metering Electricity Customer Behaviour Trials (CBTs) project. This project is initiated by the Commission for Energy Regulation (CER) [9]. This paper randomly takes 10 customers from the database to simulate the investigated energy community. The electricity and heat data readings are collected in half-hourly interval.

In the demonstration, the set of electricity tariffs are the typical UK TOU tariffs that are invented by ELEXON in the 1990s [10]. This set of TOU tariffs are designed from the nationwide wholesale prices of electricity across the UK. The seasonal tariffs are shown in fig. 3:

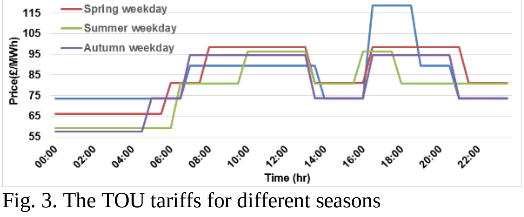

Fig. 3. The TOU tariffs for different seasons

In the scenarios of CHP system, a controllable ES is installed in-home to provide flexibility. A constant price is adopted for gas. We assume unified parameters of both CHP units, whose electricity/heat capacity is 1/0.8 kW, and ES, which is concluded in Table I [11]:

TABLE I

ENERGY STORAGE PARAMETERS

Hardware parameters	*Unit*
Battery Capacity	6 kWh
Battery Charging Limit	1.5 kW
Battery Discharging Limit	1.5 kW
Battery Max SOC	100%
Battery Min SOC	10%
Battery Charging Efficiency	0.9
Battery Discharging Efficiency	0.9

Benchmarks

In this paper, the performance of CHP system is assessed under two categories of benchmarks: i) the energy costs; and ii) the peak and uncertainty of demand. In general, the energy costs are the objectives that are considered in most of the prior works, whilst the peak and uncertainty are the system level objectives that are concerned by the whole energy community. The second category of benchmarks that indicate the system peak and uncertainty of demand are introduced in the objective of proposed model ($P2$). The peak is represented as the maximum of net demand $x_t \in X$.

$$Peak = \max(X) \qquad (17)$$

The uncertainty of net demand can be represented as the standard deviation (SD) σ with respect to arithmetic mean of net demand.

$$\sigma(X) = E[(X-E[X])^2] = \sqrt{\frac{\sum_{t=1}^{T}(x_t-E[X])^2}{T}} \qquad (18)$$

DEMONSTRATION

To validate the proposed decentralized dispatch strategy, the performance of proposed model ($P2$) is compared to the traditional strategy that only focuses on the cost minimization of gas and electricity ($P1$). The results are arranged in two parts: i) performance comparison of individual prosumers; ii) and performance comparison of the energy community.

Performance of individual prosumers

Performance of individual prosumers by the two models are shown in Fig. 4 and Fig. 5.

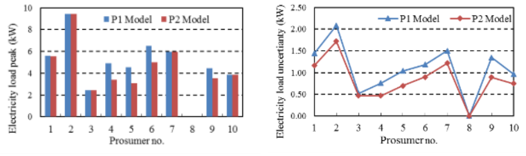

Fig. 4. The peaks and uncertainty of prosumers net electricity load

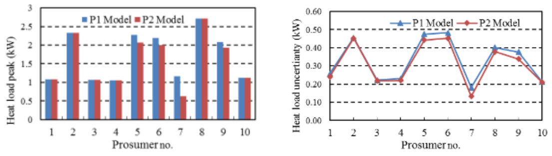

Fig. 5. The peaks and uncertainty of prosumers net heat load

The result indicates both peak and uncertainty of prosumer demand under the proposed strategy are decreased. Compared to traditional strategy, the result indicates L_2-norm term added in model $P2$ shifts energy from peak periods to low demand periods and flattens both electricity and heat demand curves.

Performance of the energy community

Performance of the energy community by the two models is given in Fig. 6 and Table. II.

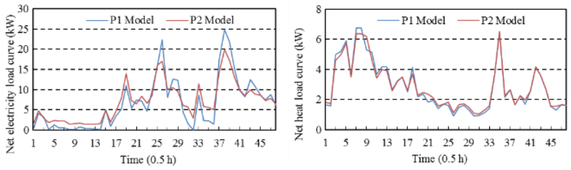

Fig. 6. Demand curves of electricity and heat in the energy community

TABLE II

PEAK AND UNCERTAINTY OF ELECTRICITY AND HEAT DEMAND

Model	*Electricity Peak* (kW)	*Electricity SD* (kW)	*Heat Peak* (kW)	*Heat SD* (kW)
Original	26.49	6.05	13.6	3.14
Model P1	24.80	6.37	2.88	1.63
Model P2	19.85	4.76	2.85	1.51

As shown in the Table III, model $P1$ which designed to minimize the energy cost, will have an adverse impact on the system regarding system uncertainty, i.e., increases the system uncertainty from 6.05 to 6.37. This is because the aggregation of demand curve will lack smoothness, which affects the uncertainty of system demand.

Compared to model $P1$, proposed model $P2$ can bring peak and uncertainty reduction to the system. In detail, it can damp down 20% and 1% of the peak of system electricity and heat demand, respectively. In terms of uncertainty reduction, the proposed model $P2$ can reduce 25% and 7% of uncertainty in system electricity and heat demand. It is notable that the proposed decentralized dispatch strategy will largely reduce the peak and uncertainty of system electricity and heat demand.

CONCLUSION

This paper for the first time explores the functionality of household EMS strategy with ES and CHP units to support system peak and uncertainty management in a decentralized fashion. A novel model considering L_2-norm term in the dispatch objective is proposed as the control strategy of the household demand curves. The proposed strategy is compared to classical min-cost strategy.

Performances are validated on two aspects: i) performance of individual prosumers; ii) performance of the energy community. Compared to classical strategy, the result indicates L_2-norm term added in the proposed model can shift energy from peak periods to low demand periods and flatten household demand curves. The proposed strategy can damp down 20% and 1% of the peak of system electricity and heat demand, respectively. It also reduces the uncertainty in system electricity and heat demand by 25% and 7%, respectively. According to the comparison across scenarios, the decentralized household EMS strategy can achieve system level targets, i.e., system peak and uncertainty reduction, in a decentralized way.

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