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Cyber-Physical Model for Efficient and Secured Operation of CPES or Energy Internet

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1.1. Description of the Case Study

We tested the proposed cyber-physical energy system (CPES) based on a network of four buildings. The structure of the network is shown in Fig. 1 (c) of the main document. There are totally six energy transmission lines, namely TR12, TR13, TR14, TR23, TR24, and TR34, respectively. For example, TR12 represents the transmission line between building 1 and 2. The energy losses of the transmission lines are 2%, 4%, 9%, 5%, 7%, and 3%, respectively. As mentioned in the main document, all the four buildings can exchange energy with the power grid individually. So in the CPES model developed in the main document, there are five nodes which are coordinator and buildings 1-4 respectively (as shown in Fig. 1 (c)). In this case, the time-of-use (TOU) electricity price, the price of energy fed into the power grid, the number of the rooms in each building, the capacity of the battery, the size of the PV panel in each building and the mean power of the washer can be found in [7] of the main document. The communication delay and data dropout are ignored and the weights for the information exchange between all buildings and the coordinator are set to 1, and others are set to 0. The weights for the energy exchange among the buildings are determined by the energy loss of each transmission line. The optimization problem of the building node i is given by:

$$\min_{\mathbf{U}_i} J_i(\overset{\leftarrow k}{\mathbf{x}}_i, \mathbf{U}_i), \quad \text{with}$$

$$J_i(\overset{\leftarrow k}{\mathbf{x}}_i, \mathbf{U}_i) = \sum_{k=1}^{K}[c_d^k e_{d,i}^k - c_u^k e_{u,i}^k + C_{b,i}^k + \sum_{\langle i,j\rangle \in \mathbf{E}_b} \overset{\leftarrow k}{\mathbf{x}}_{i,j}(e_{\leftarrow j}^{i,k} - e_{\rightarrow j}^{i,k} \cdot \gamma_{\langle i,j\rangle})], \tag{1}$$

s.t. Equations (1)-(28) in the reference [7] of the main document,

where i and j are the indices of the buildings with i, j=1,2,3,4; k is the stage index with k=1,2,…,K; $J_i(\overset{\leftarrow k}{\mathbf{x}}_i, \mathbf{U}_i)$ is the overall energy cost of the building i; $\mathbf{U}_i$ is the vector of the decision variables for building i, which is defined in [7] of the main document; $\overset{\leftarrow k}{\mathbf{x}}_i$ is defined as $\overset{\leftarrow k}{\mathbf{x}}_i = (\overset{\leftarrow k}{\mathbf{x}}_{i,1}, \overset{\leftarrow k}{\mathbf{x}}_{i,2}, \ldots, \overset{\leftarrow k}{\mathbf{x}}_{i,4})^T$, which indicates the information obtained from the coordinator for building i at k; c_d^k is the price of electricity bought from the power grid at k; $e_{d,i}^k$ is the energy supplied from the power grid to building i at k; c_u^k is the price of electricity fed into the power grid at k; $e_{u,i}^k$ is the energy sold to the power grid from building i at k; $C_{b,i}^k$ is the penalty of the cycle lifetime for the battery in building i at k; $\mathbf{E}_b$ is the edge set of the four buildings; $\overset{\leftarrow k}{\mathbf{x}}_{i,j}$ is the information obtained from the coordinator for the energy exchange between building i and j at k; $e_{\leftarrow j}^{i,k}$ is the energy supplied from building j to building i at k; $e_{\rightarrow j}^{i,k}$ is the energy sold to building j from building i at k; and $\gamma_{\langle i,j\rangle}$ is the coefficient for the energy loss of the transmission line between buildings i and j.

As mentioned in the main document, the information updating of the coordinator node is performed by the subgradient method. So the traffic model can be given by:

$$\overset{\leftarrow k,l+1}{\mathbf{x}}_{i,j} = \overset{\leftarrow k,l}{\mathbf{x}}_{i,j} + s^l(e_{\leftarrow j}^{i,k,l} - e_{\rightarrow j}^{i,k,l} \cdot \gamma_{\langle i,j\rangle} - e_{\rightarrow i}^{j,k,l} \cdot \gamma_{\langle i,j\rangle} + e_{\leftarrow i}^{j,k,l}), \tag{2}$$

where superscript l is the iteration index; and s^l is the step size for the information updating. By iteratively calculating (1)-(2), the solution for the problem can be obtained until the calculation converges. Since the sugradient method is used in the process of information updating, the convergence can be guaranteed [S1].

1.2. Numerical Results

The test is conducted for a deterministic version of the problem, in which the solar radiation is assumed to be exactly forecasted and obtained from [S2]. In this case, the problem of (1) for each building is solved by using the CPLEX solver with the relative error gap being 0.01. The calculation is carried out on a Windows PC with 3.2 GHz CPU and 16 GB memory.

The problem with the forecasted solar radiation over the scheduling horizon (K=48, i.e., 24 hours are divided into 48 stages) is solved, and the results are shown in Table 1. The calculation of the node and traffic model converges after the 39-th iteration, which took about 270 seconds to obtain the solution. In Table 1, it is found that the dual gap is very small. It reveals that the method developed in the main document can efficiently find a good solution.

Furthermore, to analyze the performance of the CPES, we also solve the individual optimization problem of each building. Note that in the case of the individual optimization, the energy exchange among the buildings is not involved, and any buildings manage their operation individually. The overall cost of the individual optimization is also shown in Table 1. It is found that about 7.6% of the overall energy cost of these buildings can be saved by the joint optimization based on the CPES framework as compared to the individual optimization. It means that the joint optimization based on the CPES framework can further improve the energy efficiency of the whole system.

Table 1. Performance Analysis of the Developed CPES Framework

Overall cost of the considered problem (S$)	2662.8
Cost of the Lagrangian relaxation dual problem for the considered problem (S$)	2609.4
Dual gap of the above two solutions	2.0%
Overall cost of the individual optimization (S$)	2881.1

References

[S1] X. Guan, P. B. Luh, H. Yan, and A. Amalfi, “An optimization-based method for unit commitment,” International Journal of Electrical Power & Energy Systems, 14(1): 9-17, 1992.

[S2] http://www.weather.gov.sg/