Combinatorial clock exchange for local energy markets: Online appendices

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Appendix A
Prosumer models

In this section, we describe the preferred package problem for prosumers owning different assets and trading energy, flexibility or both. Let $\mathcal{H} := \{1, \dots, h\}$ denote the set of time slots. Then, the set of products $\mathcal{M}$ has $m = h$ products in case of and energy only market and $m = 2h$ products in case of joint energy and flexibility market.

A. Renewable power producer (energy)

Renewable power producer represents a wind or a solar power producer that is interested in selling energy in the local market. The opportunity price $\underline{\boldsymbol{\lambda}}$ is typically low and characterizes the value for its energy in the local market. The prosumer seeks to get a better price in the local market. Let $\mathbf{g}$ denote the forecasted generation for each time slot, then the preferred package problem reads as

$$\max_{\mathbf{x}} \ \langle \underline{\boldsymbol{\lambda}}^o - \boldsymbol{\lambda}, \mathbf{x} \rangle \tag{1a}$$

$$\text{s.t. } -\mathbf{g}_j \le \mathbf{x}_j \le 0, \ \forall j \in \{1, \dots, m\} \tag{1b}$$

B. Consumer (energy)

A consumer owns energy consuming devices and is interested in fulfilling its consumption requirements while minimizing monetary costs. The prosumer seeks to get a lower price than $\bar{\boldsymbol{\lambda}}$ in the local market. Let $\mathbf{g}$ denote its forecasted consumption for each time slot, then the preferred package problem reads as

$$\max_{\mathbf{x}} \ \langle \bar{\boldsymbol{\lambda}}^o - \boldsymbol{\lambda}, \mathbf{x} \rangle \tag{2a}$$

$$\text{s.t. } 0 \le \mathbf{x}_j \le \mathbf{g}_j, \ \forall j \in \{1, \dots, m\} \tag{2b}$$

C. Storage (energy)

Here, we describe the model for an energy storage resource that is interested only in trading energy as opposed to the storage model in section **??** trading energy and flexibility. Moreover, here we model some more aspects of a storage resource such as charge/discharge efficiency, cyclic degradation, self discharge, availability, and charge/discharge rate limits. The preferred package problem reads as

$$\max_{\mathbf{x},\mathbf{s},\boldsymbol{\delta}} \ \langle \bar{\boldsymbol{\lambda}}^o, \mathbf{x} \odot \boldsymbol{\delta} \rangle + \langle \underline{\boldsymbol{\lambda}}^o, \mathbf{x} \odot (\mathbf{1} - \boldsymbol{\delta}) \rangle - \beta \|\mathbf{x}\|_1 - \|\mathbf{s} - \hat{\mathbf{s}}\|_{\boldsymbol{\alpha}} - \langle \boldsymbol{\lambda}, \mathbf{x} \rangle \tag{3a}$$

$$\text{s.t. } \mathbf{x}_j \le M \boldsymbol{\delta}_j, \ \forall j \in \mathcal{H} \tag{3b}$$

$$\mathbf{x}_j \ge -M(1 - \boldsymbol{\delta}_j), \ \forall j \in \mathcal{H} \tag{3c}$$

$$\mathbf{s}_{j-1} + \eta \mathbf{x}_j - \boldsymbol{\gamma}_j - M(1 - \boldsymbol{\delta}_j) \le \mathbf{s}_j \le \mathbf{s}_{j-1} + \eta \mathbf{x}_j - \boldsymbol{\gamma}_j + M(1 - \boldsymbol{\delta}_j), \ \forall j \in \mathcal{H} \tag{3d}$$

$$\mathbf{s}_{j-1} + \mathbf{x}_j/\eta - \boldsymbol{\gamma}_j - M(1 - \boldsymbol{\delta}_j) \le \mathbf{s}_j \le \mathbf{s}_{j-1} + \mathbf{x}_j/\eta - \boldsymbol{\gamma}_j + M(1 - \boldsymbol{\delta}_j), \ \forall j \in \mathcal{H} \tag{3e}$$

$$0 \le \mathbf{s}_j \le \bar{s}, \ \forall j \in \mathcal{H} \tag{3f}$$

$$\underline{x} \le \mathbf{x}_j \le \bar{x}, \ \forall j \in \mathcal{H} \tag{3g}$$

$$-M\mathbf{a}_j \le \mathbf{x}_j \le M\mathbf{a}_j, \tag{3h}$$

$$\boldsymbol{\delta}_j \in \{0, 1\}, \ \forall j \in \mathcal{H} \tag{3i}$$

where $\odot$ denotes elementwise multiplication, and M is a big number. The first two terms in the objective (3a) denote the opportunity cost of trading package $\mathbf{x}$ with an external entity. The third term represents cyclic degradation with coefficient β. $\boldsymbol{\delta}_j$ denotes a binary variable that is 1 if charging and 0 if discharging, due to (3b),(3c). Constraints (3d),(3e) represent state-of-charge dynamics with efficiency η and self discharge $\boldsymbol{\gamma}$. (3f),(3g) represent storage capacity and charging rate constraints. Constraint (3h) enforces availability constraint that can model disconnection, for instance, and electric vehicle (EV) not plugged in.

The model described above is a generic storage model that can model specific devices like thermal inertia with heat pump, EV, and home batteries, through appropriate parameters $\beta, \boldsymbol{\gamma}, \eta, \boldsymbol{\alpha}, \mathbf{a}, \bar{s}, \bar{x}, \underline{x}$. For instance, in a building thermal inertia model, self discharge would represent insulation losses, $\bar{s}$ represent thermal mass corresponding to the allowed temperature variation, and $\underline{x} = 0$.

D. Switched load (energy)

Devices like dishwashers, laundry machines, and industrial processes can be modeled as fixed volume loads with volume L that requires t_r slots to complete, once switched on. Let the desired time slot range for load completion be $[t_l, t_u]$, i.e., the load can be started earliest in slot $t_l \in \mathcal{H}$ and must be completed by the end of slot $t_u \in \mathcal{H}$. An important aspect is that the load can not be stopped and must run to completion once switched on. For instance, many industrial processes can not be distributed over time. The preferred package problem for a switched load reads as

$$\max_{\mathbf{x}} \langle \bar{\boldsymbol{\lambda}}^o - \boldsymbol{\lambda}, L\boldsymbol{\delta} \rangle \tag{4a}$$

$$\text{s.t.} \sum_{j=k}^{k+t_r-1} \boldsymbol{\delta}_j \geq z_k t_r, \ \forall k \in \{t_l, t_u - t_r + 1\} \tag{4b}$$

$$\sum_{k=t_l}^{t_u-t_r+1} z_k \geq 1 \tag{4c}$$

$$\mathbf{x}_j = L\boldsymbol{\delta}_j \tag{4d}$$

$$\boldsymbol{\delta}_j, z_k \in \{0,1\}, \ \forall j \in \mathcal{M}, k \in \{t_l, t_u - t_r + 1\}, \tag{4e}$$

where $\boldsymbol{\delta}_j$ indicates the switch state of load in slot j. z_k indicates whether the load ran to completion starting in slot k due to (4b) and constraint (4c) enforces load completion at least once.

E. DSO (flexibility)

Here, we model a distribution system operator (DSO) that is interested in procuring flexibility services from prosumers in the distribution network. Let $\bar{x}$ denote the maximum flexibility requirement, and $\boldsymbol{\alpha}$ denote a parameter representing diminishing marginal value due to uncertainty in real-time imbalances. The corresponding preferred package problem reads as

$$\max_{\mathbf{x}} \langle \bar{\boldsymbol{\lambda}}^o - \boldsymbol{\lambda}, \mathbf{x} \rangle - \|\mathbf{x}\|_{\boldsymbol{\alpha}} \tag{5a}$$

$$\text{s.t. } 0 \leq \mathbf{x}_j \leq \bar{x}, \ \forall j \in \{1, \ldots, h\}. \tag{5b}$$

$$\tag{5c}$$