연구노트

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장서현[1]

[1]**SY**stems **M**odeling and **P**rogramming **L**ab at **Y**onsei University (**SYMPLY**)
연세대학교 산업공학과
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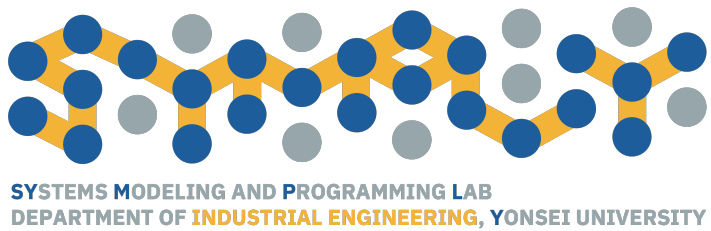

Background

Individual DER Participation 모델의 한계

- 개별적 DER 포토폴리오 운영의 실질적 한계

Aggregated DER Participation 모델의 한계

- 모델 내에서 pooling의 과정이 추상적으로 이루어지기 때문에, 각 DER 소유자가 어떻게 기여하는지 알 수 없음
- 차후 수익 분배 및 페널티 부담 문제를 고려하면 이를 구체적으로 모델링할 필요가 있음

Solution of Part 2

1. Aggregated level에서 최적화를 진행하되, Aggregated DER Participation 모델이 설명하지 못한 각 개인의 커밋량 및 에너지 거래 내역을 결정해야함

⇒ **Settlement Phase**의 필요성

2. Settlement Phase를 최적화 과정에서 고려할 수 있도록 수리모델을 확장해야 함

⇒ **수리모델 확장**의 필요성

Settlement Phase

Decision Variables

- $d_{ijt}(\xi)$: Amount of surplus energy transferred from individual i to individual j at hour t
- $e_{it}^{+}(\xi)$: Amount of surplus energy of individual i at hour t after settlement
  - Aggregation 모델의 $\beta_t^{+}(\xi)$의 역할
- $e_{it}^{-}(\xi)$: Amount of shortage energy of individual i at hour t after settlement
  - Aggregation 모델의 $\beta_t^{-}(\xi)$의 역할

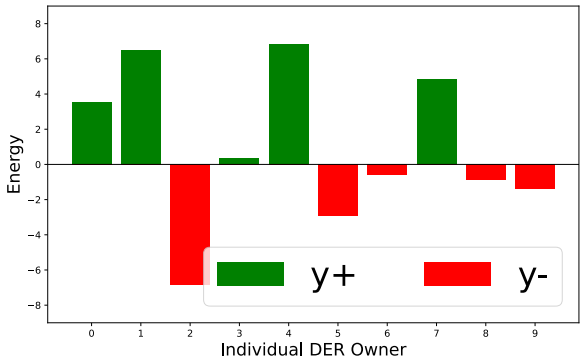

Figure 9: Pre-Settlement

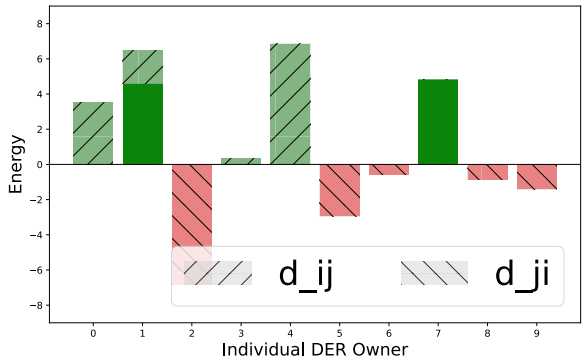

Figure 10: Settlement Process

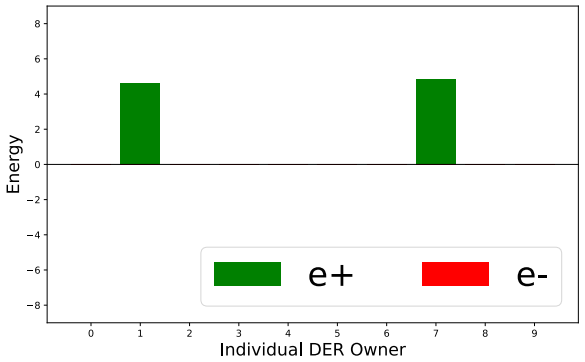

Figure 11: Post-Settlement

Aggregated DER Settlement Model (1/4)

Framework

(1) First-Stage Decision: 개별 day ahead commitment 양 결정 (x_{it}^{DA})

- α_t^{DA} 를 $\sum_{i \in I} x_{it}^{DA}$ 로 대체

(2) Second-Stage Decisions

- Pre-Settlement: commitment 후에 남는 initial surplus ($y_{it}^{+}(\xi)$) / shortage ($y_{it}^{-}(\xi)$) 결정
- Settlement Phase: DER 사업자들 간 에너지 거래량 ($d_{ijt}(\xi)$) 결정
- Post-Settlement: 에너지 거래 후 settled surplus ($e_{it}^{+}(\xi)$) / shortage ($e_{it}^{-}(\xi)$) 결정

Objective Function: Maximize Aggregated Profit

$$\max \quad \sum_{t \in T} \left(P_t^{DA} \sum_{i \in I} x_{it}^{DA} + \mathbb{E} \left[P_t^{RT}(\xi_s) \sum_{i \in I} e_{it}^{+}(\xi_s) - P_t^{PN} \sum_{i \in I} e_{it}^{-}(\xi_s) \right] \right) \tag{3a}$$

(3a) Profit = Day-ahead Commitment Revenue $\left(\sum_{t \in T} \left(P_t^{DA} \sum_{i \in I} x_{it}^{DA} \right) \right)$

+ Real-time Trading Revenue $\left(\sum_{t \in T} \left(P_t^{RT}(\xi) \sum_{i \in I} e_{it}^{+}(\xi) \right) \right)$

- Commitment Breach Cost $\left(\sum_{t \in T} \left(P_t^{PN} \sum_{i \in I} e_{it}^{-}(\xi) \right) \right)$

Aggregated DER Settlement Model (2/4)

Constraints: Pre-Settlement

$$R_{it}(\xi_s) - x_{it}^{DA} = y_{it}^{+}(\xi_s) - y_{it}^{-}(\xi_s) \quad \forall i \in I, \forall t \in T \tag{3b}$$

$$R_{it}(\xi_s) \geq y_{it}^{+}(\xi_s) \quad \forall i \in I, \forall t \in T \tag{3c}$$

$$y_{it}^{+}(\xi_s) \leq M^{y} z_{it}^{y}(\xi_s), \quad y_{it}^{-}(\xi_s) \leq M^{y}(1 - z_{it}^{y}(\xi_s)) \quad \forall i \in I, \forall t \in T \tag{3d}$$

(3b) 자신의 residual energy와 commitment 양에 따라 initial surplus/shortage 양이 결정됨

(3c) 자신이 real-time market에 판매할 수 있는 양은 자신의 residual energy보다 작아야함

(3d) y^{+}와 y^{-}는 동시에 발생할 수 없음

Constraints: Settlement Phase

$$\sum_{j \in I, j \neq i} d_{ijt}(\xi_s) \leq y_{it}^{+}(\xi_s), \quad \sum_{j \in I, j \neq i} d_{jit}(\xi_s) \leq y_{it}^{-}(\xi_s) \quad \forall i \in I, \forall t \in T \tag{3e}$$

$$d_{iit}(\xi_s) = 0 \quad \forall i \in I, \forall t \in T \tag{3f}$$

(3e) 자신이 줄 수 있는 양은 자신의 initial surplus보다 작아야하며, 자신이 받을 수 있는 양은 자신의 initial shortage보다 작아야함

(3f) 자기 자신과 거래할 수 없음

Aggregated DER Settlement Model (3/4)

Constraints: Post-Settlement

$$e_{it}^{+}(\xi_s) = y_{it}^{+}(\xi_s) - \sum_{j \in I, j \neq i} d_{ijt}(\xi_s) \quad \forall i \in I, \forall t \in T \tag{3g}$$

$$e_{it}^{-}(\xi_s) = y_{it}^{-}(\xi_s) - \sum_{j \in I, j \neq i} d_{jit}(\xi_s) \quad \forall i \in I, \forall t \in T \tag{3h}$$

(3g) (3h) 개별 DER의 settled surplus/shortage는 에너지 거래 결과에 의해 결정됨

Constraints: Aggregated Market Participation

$$\sum_{i \in I} R_{it}(\xi_s) - \sum_{i \in I} x_{it}^{DA} = \sum_{i \in I} e_{it}^{+}(\xi_s) - \sum_{i \in I} e_{it}^{-}(\xi_s) \quad \forall t \in T \tag{3i}$$

$$\sum_{i \in I} R_{it}(\xi_s) \geq \sum_{i \in I} e_{it}^{+}(\xi_s) \quad \forall t \in T \tag{3j}$$

$$\sum_{i \in I} e_{it}^{+}(\xi_s) \leq M^e z_t^e(\xi_s), \quad \sum_{i \in I} e_{it}^{-}(\xi_s) \leq M^e (1 - z_t^e(\xi_s)) \quad \forall t \in T \tag{3k}$$

(3i) Aggregated residual과 commitment에 의해 aggregator의 surplus/shortage가 결정됨

(3j) Aggregator가 real-time market에 판매할 수 있는 양은 aggregated surplus보다 작아야함

(3k) Aggregated level에서의 surplus와 shortage는 동시에 발생할 수 없음

Aggregated DER Settlement Model (4/4)

$$\max \quad \sum_{t\in T}\left(P_t^{DA}\sum_{i\in I}x_{it}^{DA}+\mathbb{E}\left[P_t^{RT}(\xi_s)\sum_{i\in I}e_{it}^{+}(\xi_s)-P_t^{PN}\sum_{i\in I}e_{it}^{-}(\xi_s)\right]\right) \tag{3a}$$

$$\text{s.t.} \quad R_{it}(\xi_s)-x_{it}^{DA}=y_{it}^{+}(\xi_s)-y_{it}^{-}(\xi_s) \quad \forall i\in I,\forall t\in T \tag{3b}$$

$$R_{it}(\xi_s)\geq y_{it}^{+}(\xi_s) \quad \forall i\in I,\forall t\in T \tag{3c}$$

$$y_{it}^{+}(\xi_s)\leq M^{y}z_{it}^{y}(\xi_s),\quad y_{it}^{-}(\xi_s)\leq M^{y}(1-z_{it}^{y}(\xi_s)) \quad \forall i\in I,\forall t\in T \tag{3d}$$

$$\sum_{j\in I,j\neq i}d_{ijt}(\xi_s)\leq y_{it}^{+}(\xi_s),\quad \sum_{j\in I,j\neq i}d_{jit}(\xi_s)\leq y_{it}^{-}(\xi_s) \quad \forall i\in I,\forall t\in T \tag{3e}$$

$$d_{iit}(\xi_s)=0 \quad \forall i\in I,\forall t\in T \tag{3f}$$

$$e_{it}^{+}(\xi_s)=y_{it}^{+}(\xi_s)-\sum_{j\in I,j\neq i}d_{ijt}(\xi_s) \quad \forall i\in I,\forall t\in T \tag{3g}$$

$$e_{it}^{-}(\xi_s)=y_{it}^{-}(\xi_s)-\sum_{j\in I,j\neq i}d_{jit}(\xi_s) \quad \forall i\in I,\forall t\in T \tag{3h}$$

$$\sum_{i\in I}R_{it}(\xi_s)-\sum_{i\in I}x_{it}^{DA}=\sum_{i\in I}e_{it}^{+}(\xi_s)-\sum_{i\in I}e_{it}^{-}(\xi_s) \quad \forall t\in T \tag{3i}$$

$$\sum_{i\in I}R_{it}(\xi_s)\geq\sum_{i\in I}e_{it}^{+}(\xi_s) \quad \forall t\in T \tag{3j}$$

$$\sum_{i\in I}e_{it}^{+}(\xi_s)\leq M^{e}z_{t}^{e}(\xi_s),\quad \sum_{i\in I}e_{it}^{-}(\xi_s)\leq M^{e}(1-z_{t}^{e}(\xi_s)) \quad \forall t\in T \tag{3k}$$

$$x_{it}^{DA}\geq 0, y_{it}^{+}(\xi_s)\geq 0, y_{it}^{-}(\xi_s)\geq 0, d_{ijt}(\xi_s)\geq 0, e_{it}^{+}(\xi_s)\geq 0, e_{it}^{-}(\xi_s)\geq 0 \quad \forall i\in I,\forall t\in T,\forall s\in S \tag{3l}$$

$$z_{it}^{y}(\xi_s)\in\{0,1\}, z_{t}^{e}(\xi_s)\in\{0,1\} \quad \forall i\in I,\forall t\in T,\forall s\in S. \tag{3m}$$

Illustration of Settlement Model

[10명의 DER 소유자, 15시, 시나리오 10]

Table 5: Pre-Settlement

Agg. Model	α	β^+	β^-
Aggregator	35.64	9.45	0
Set. Model	x	y^+	y^-
DER 0	3.53	3.53	0
DER 1	5.23	6.5	0
DER 2	10.1	0	6.83
DER 3	3.05	0.36	0
DER 4	2.42	6.85	0
DER 5	3.39	0	2.96
DER 6	3.71	0	0.57
DER 7	1.86	4.84	0
DER 8	0.87	0	0.87
DER 9	1.4	0	1.4
Aggregator	35.64	22.08	12.62

Table 6: Settlement

i	j	d
0	5	2.13
0	9	1.40
1	5	0.45
1	6	0.57
1	8	0.87
3	2	0.36
4	2	6.47
4	5	0.38

Table 7: Post-Settlement

Agg. Model	β^+	β^-
Aggregator	9.45	0
Set. Model	e^+	e^-
DER 0	0	0
DER 1	4.61	0
DER 2	0	0
DER 3	0	0
DER 4	0	0
DER 5	0	0
DER 6	0	0
DER 7	4.84	0
DER 8	0	0
DER 9	0	0
Aggregator	9.45	0

Part 2: Conclusion

Aggregated level에서 최적화된 시장 참여를 하며, Settlement의 과정을 통해 개별적 DER의 운영을 구체화할 수 있었음

Future Works

Fairness Consideration (1/2)

Aggregated DER Settlement Model의 한계점

에너지 거래 방식 및 수익 분배 과정에서 **공정성**이 보장되어야함

수익분배 측면

- 자동 정산

  1. 최적화의 결과(x_{it}, e_{it}^{+}, e_{it}^{-})대로 각 개인별 수익 계산

- 사후 정산

  2. 균등 분배

  3. 발전량과 그의 시간별 가격에 따른 가중치 기반 분배

  4. 하루 동안의 에너지 거래량에 따른 가중치 기반 분배

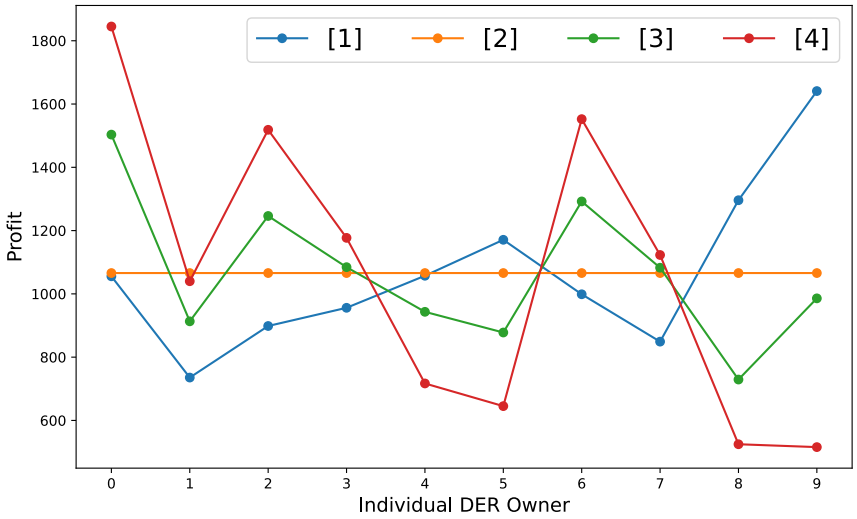

Figure 12: Profit Renumeration Approaches

Fairness Consideration (2/2)

통합 포토폴리오 운영 측면

- 시간별 기여도 제약
  → 각 시간 surplus가 있는 DER 소유자들은 shortage를 분배하여 부담해야 함

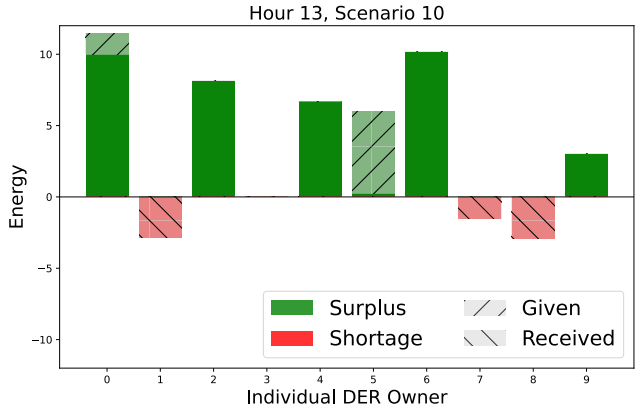

Figure 13: Violation of Hourly Balancing

- 하루별 기여도 제약
  → 하루동안 에너지를 준 양과 받은 양은 비슷해야 함

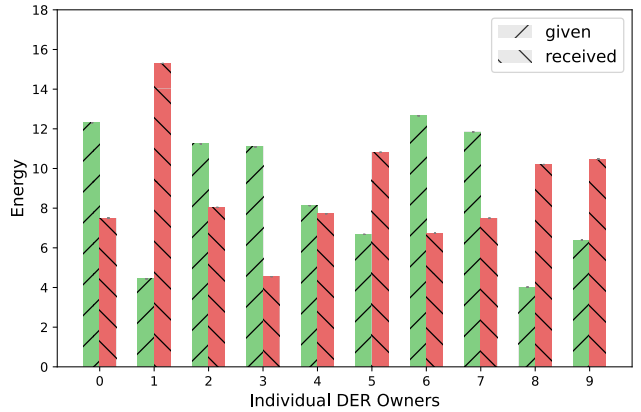

Figure 14: Violation of Daily Balancing

Future Works

Table 8: Framework for Considering Fairness

Fairness Consideration	Ex-ante (Settlement Mechanism)	Ex-post (Profit Remuneration)
Centralized Control	X	O
Decentralized Control	O O	X O

- 불확실성 및 공정성을 고려한 모델을 제안 ⇒ 공정성을 어떤 방식으로 보장해야할지 결정
- 공정성의 위반 정도를 risk factor로서 정의해서 risk-aware한 모델을 구성

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