Day-ahead Operation of an Aggregator of Electric Vehicles via Optimization under Uncertainty

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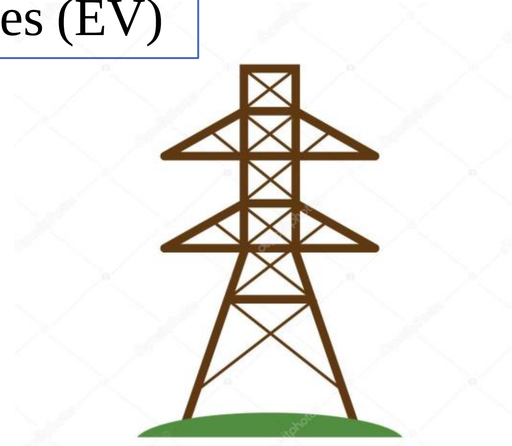
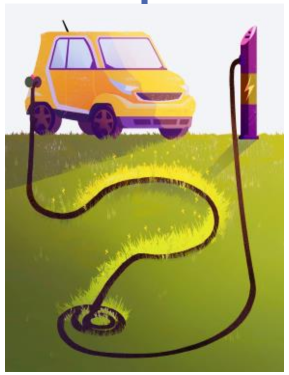
Motivation

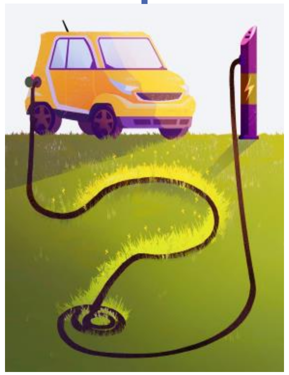
Growing penetration of Electric Vehicles (EV)

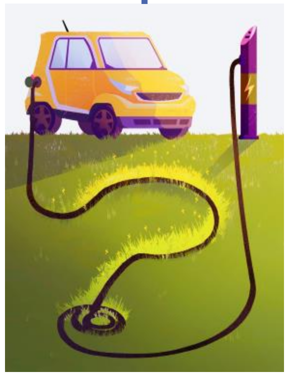
EV Aggregator



Electricity Market







EV

EV

EV

Uncertainty in Driving Patterns

Robust Optimization

Deterministic Formulation

- Objective function comprises two terms: energy bought and a penalty.
- Evolution of state of charge.
- Maximum rate of power charging.
- Maximum and minimum bounds on energy state of charge (ESOC).
- Boundary conditions for ESOC.

$$\boxed{\min_{\Xi^{DO}} \quad \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} \lambda_t c_{v,t}\Delta t + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} P\left(s^{+}_{v,t} + s^{-}_{v,t}\right)}$$

subject to:

$$\boxed{\begin{aligned} & e_{v,t} = e_{v,t-1} + \Delta t \eta_v c_{v,t} - \widehat{\xi}_{v,t} + s^{+}_{v,t} - s^{-}_{v,t}, \\ & \quad \forall t \in \mathcal{T}, v \in \mathcal{V} \end{aligned}}$$

$$\boxed{c_{v,t} \leq \overline{C}_v \widehat{\alpha}_{v,t}, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}}$$

$$\boxed{\underline{E}_v \leq e_{v,t} \leq \overline{E}_v, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}}$$

$$\boxed{e_{v,N_T} = e_{v,0}, \quad \forall v \in \mathcal{V}}$$

$$c_{v,t}, s^{+}_{v,t}, s^{-}_{v,t} \geq 0, \quad \forall v \in \mathcal{V}, t \in \mathcal{T},$$

$$\Xi^{DO} = \left(c_{v,t}, e_{v,t}, s^{+}_{v,t}, s^{-}_{v,t}\right)$$

Deterministic Formulation

Energy required for transportation

Availability of each EV

$$\min_{\Xi^{DO}} \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} \lambda_t c_{v,t}\Delta t + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} P\left(s^+_{v,t} + s^-_{v,t}\right)$$

subject to:

$$e_{v,t} = e_{v,t-1} + \Delta t \eta_v c_{v,t} - \widehat{\xi}_{v,t} + s^+_{v,t} - s^-_{v,t},$$
$$\forall t \in \mathcal{T}, v \in \mathcal{V}$$

$$c_{v,t} \leq \overline{C}_v \widehat{\alpha}_{v,t}, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\underline{E}_v \leq e_{v,t} \leq \overline{E}_v, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$e_{v,N_T} = e_{v,0}, \quad \forall v \in \mathcal{V}$$

$$c_{v,t}, s^+_{v,t}, s^-_{v,t} \geq 0, \quad \forall v \in \mathcal{V}, t \in \mathcal{T},$$

$$\Xi^{DO} = \left(c_{v,t}, e_{v,t}, s^+_{v,t}, s^-_{v,t}\right)$$

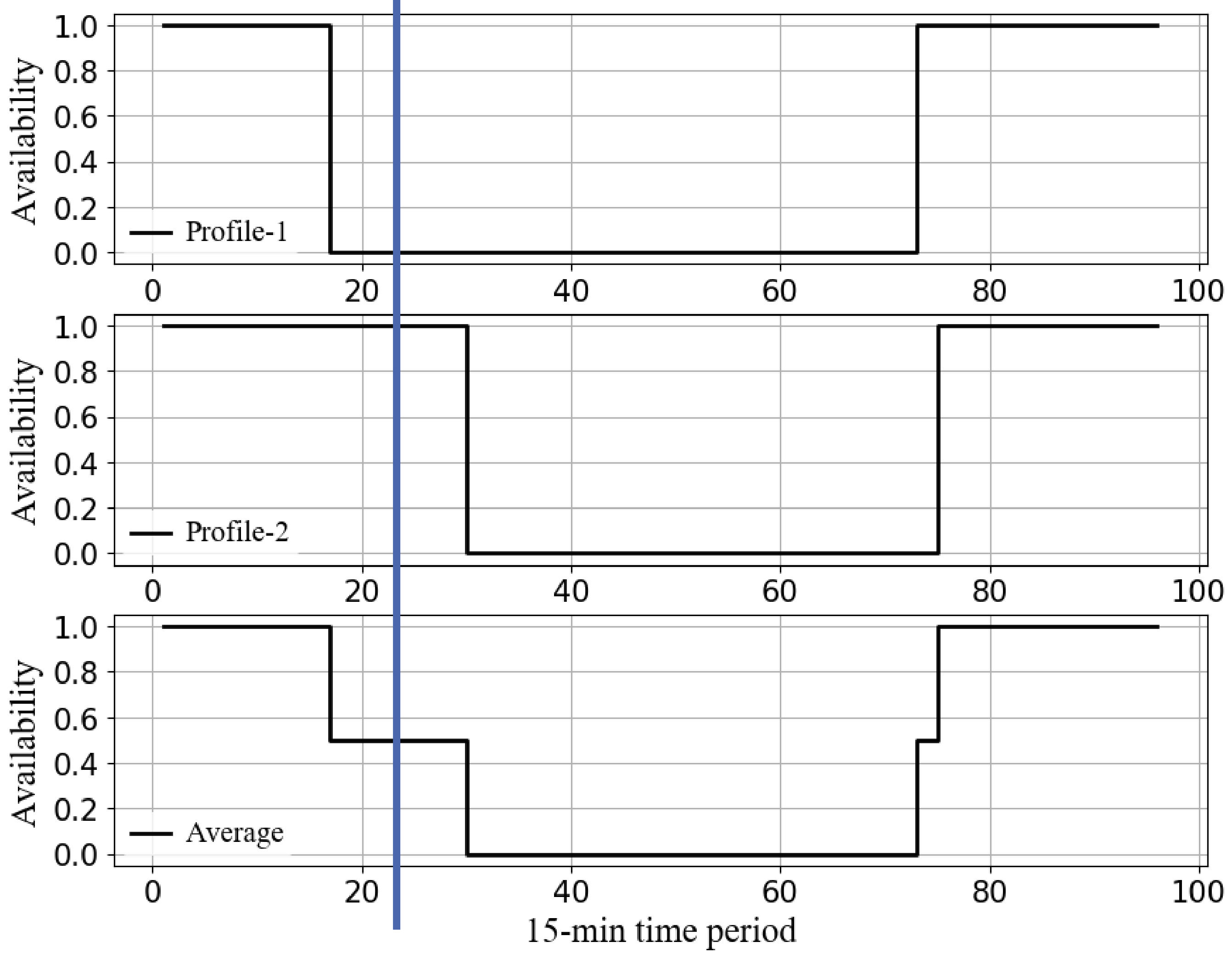
Deterministic Formulation

Availability Profiles

$$\boldsymbol{\alpha_1 = 0}$$

$$\boldsymbol{\alpha_2 = 1}$$

$$\boldsymbol{\alpha_a = 0.5}$$



Robust Formulation

- Where $\alpha_{v,t}$ is not expected value now (1 EV is available to charge, 0 is unavailable).
- $\alpha_{v,t}$ depends on an uncertain set.

Uncertainty in Driving Patterns

$$\min_{\Xi^{RB}} \sum_{v\in\mathcal{V}} \sum_{t\in\mathcal{T}} \lambda_t c_{v,t} \Delta t + \sum_{v\in\mathcal{V}} \sum_{t\in\mathcal{T}} P\left(s^+_{v,t} + s^-_{v,t}\right)$$

subject to:

$$e_{v,t} = e_{v,t-1} + \Delta t \eta_v c_{v,t} \alpha_{v,t} - \widehat{\xi}_{v,t} + s^+_{v,t} - s^-_{v,t}, \quad \forall t \in \mathcal{T}, v \in \mathcal{V}$$

$$c_{v,t} \leq \overline{C}_v, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\underline{E}_v \leq e_{v,t} \leq \overline{E}_v, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$e_{v,N_T} = e_{v,0}, \quad \forall v \in \mathcal{V}$$

$$c_{v,t}, s^+_{v,t}, s^-_{v,t} \geq 0, \quad \forall v \in \mathcal{V}, t \in \mathcal{T}$$

$$\boxed{\min_{\alpha_{v,t}} \sum_{t\in\mathcal{T}} \Delta t \eta_v c_{v,t} \alpha_{v,t} \geq \sum_{t\in\mathcal{T}} \widehat{\xi}_{v,t}, \quad \forall v \in \mathcal{V}}$$

$$\alpha_{v,t} \in \{0, 1\}, \quad \forall t \in \mathcal{T}, v \in \mathcal{V}$$

Robust Formulation

It turns into a bilevel problem

$$\min_{\alpha_{v,t}} \sum_{t\in\mathcal{T}} \Delta t\, \eta_v c_{v,t} \alpha_{v,t} \geq \sum_{t\in\mathcal{T}} \widehat{\xi}_{v,t}$$

Optimization problem

Total demand for transportation for each EV

Satisfied the demand of each EV for the worst case

Robust Formulation

- Uncertain set estimated based on historical records.

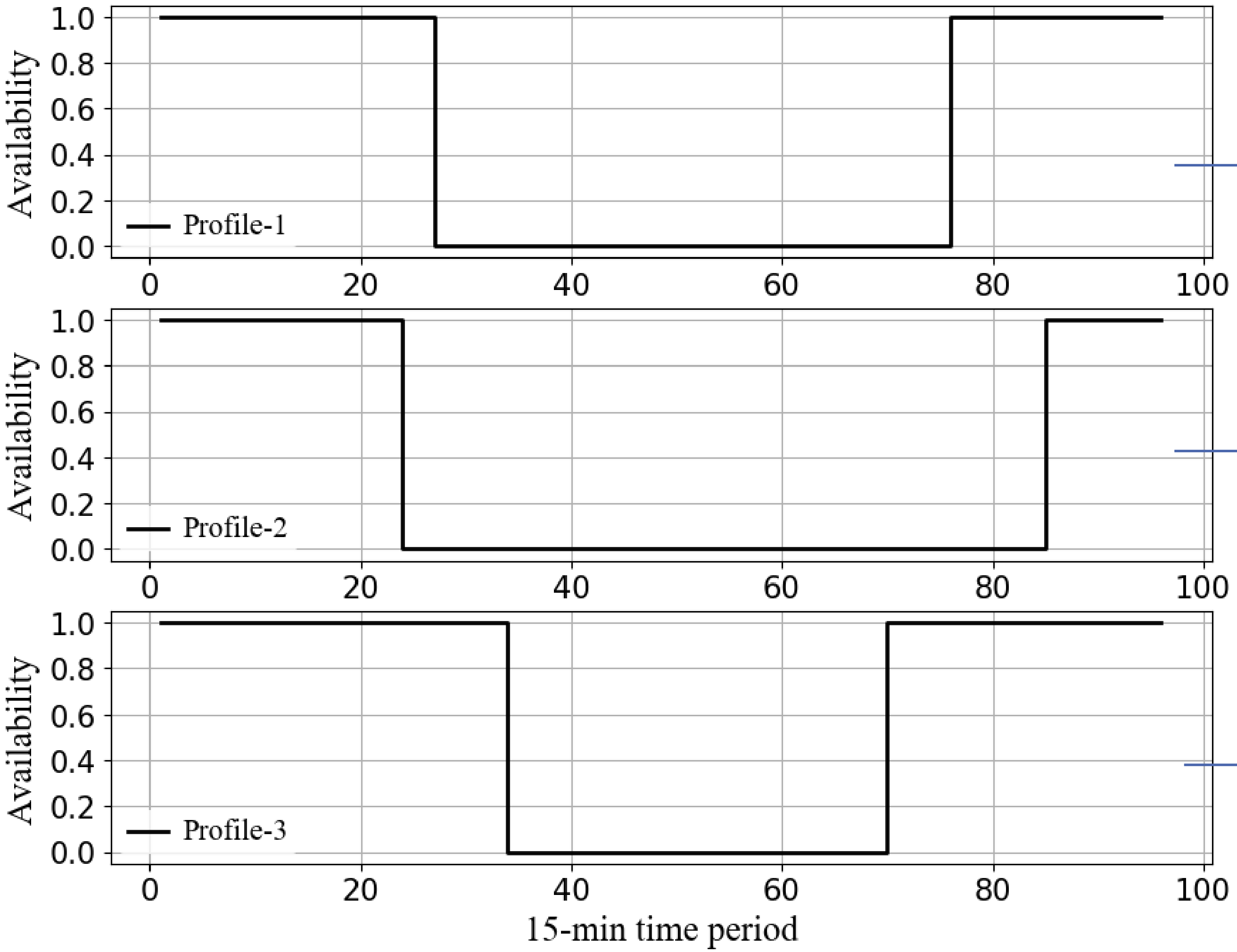
$$\sum_{t \in \mathcal{T}} \alpha_{v,t} \geq K_v \ : (\zeta_v)$$

$$\underline{\alpha}_{v,t} \leq \alpha_{v,t} \leq \overline{\alpha}_{v,t} \ : (\underline{\beta}_{v,t}, \overline{\beta}_{v,t}), \quad \forall t \in \mathcal{T}$$

Uncertainty in Driving Patterns

Robust Formulation

$$K_v = 65$$



57

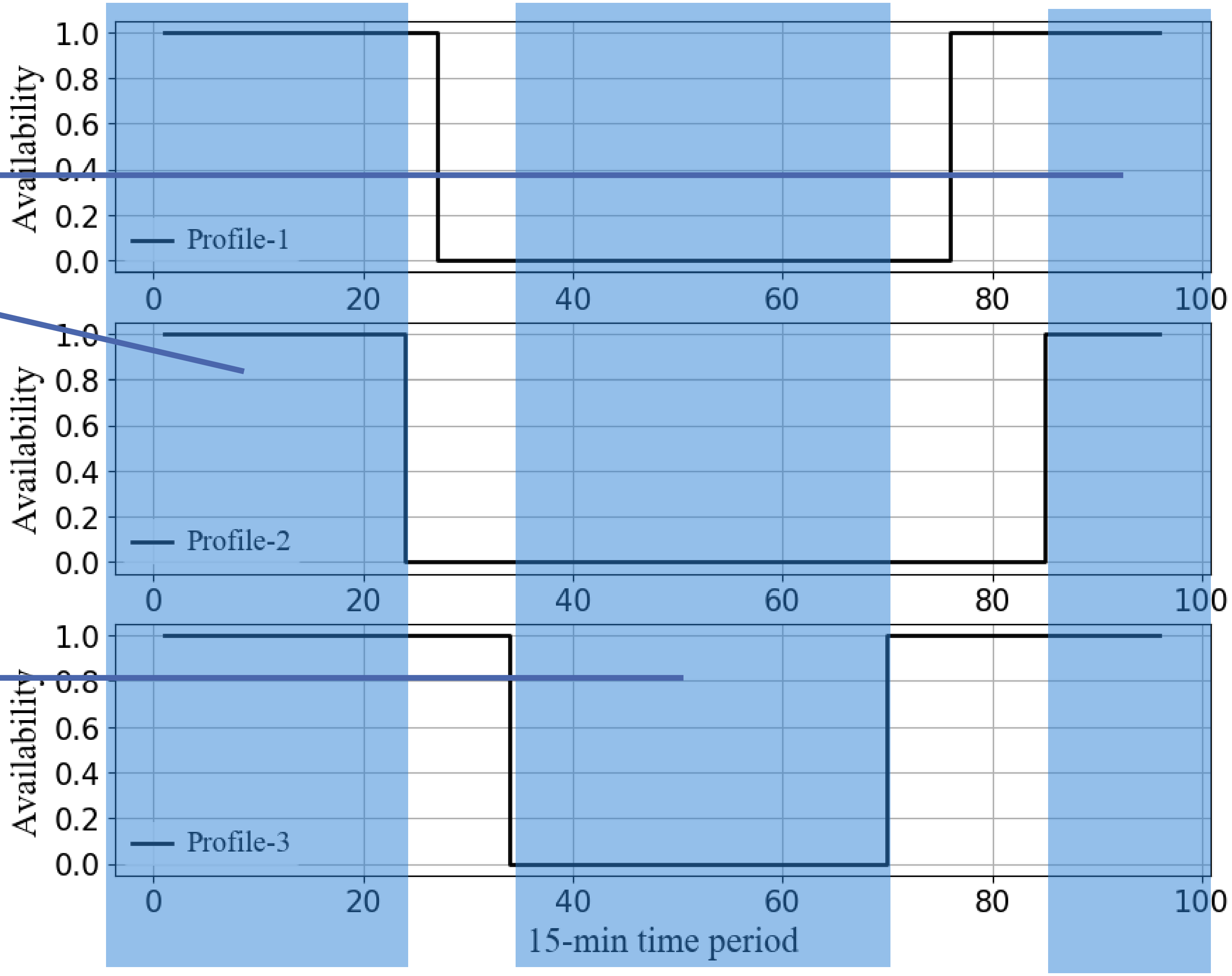
64

72

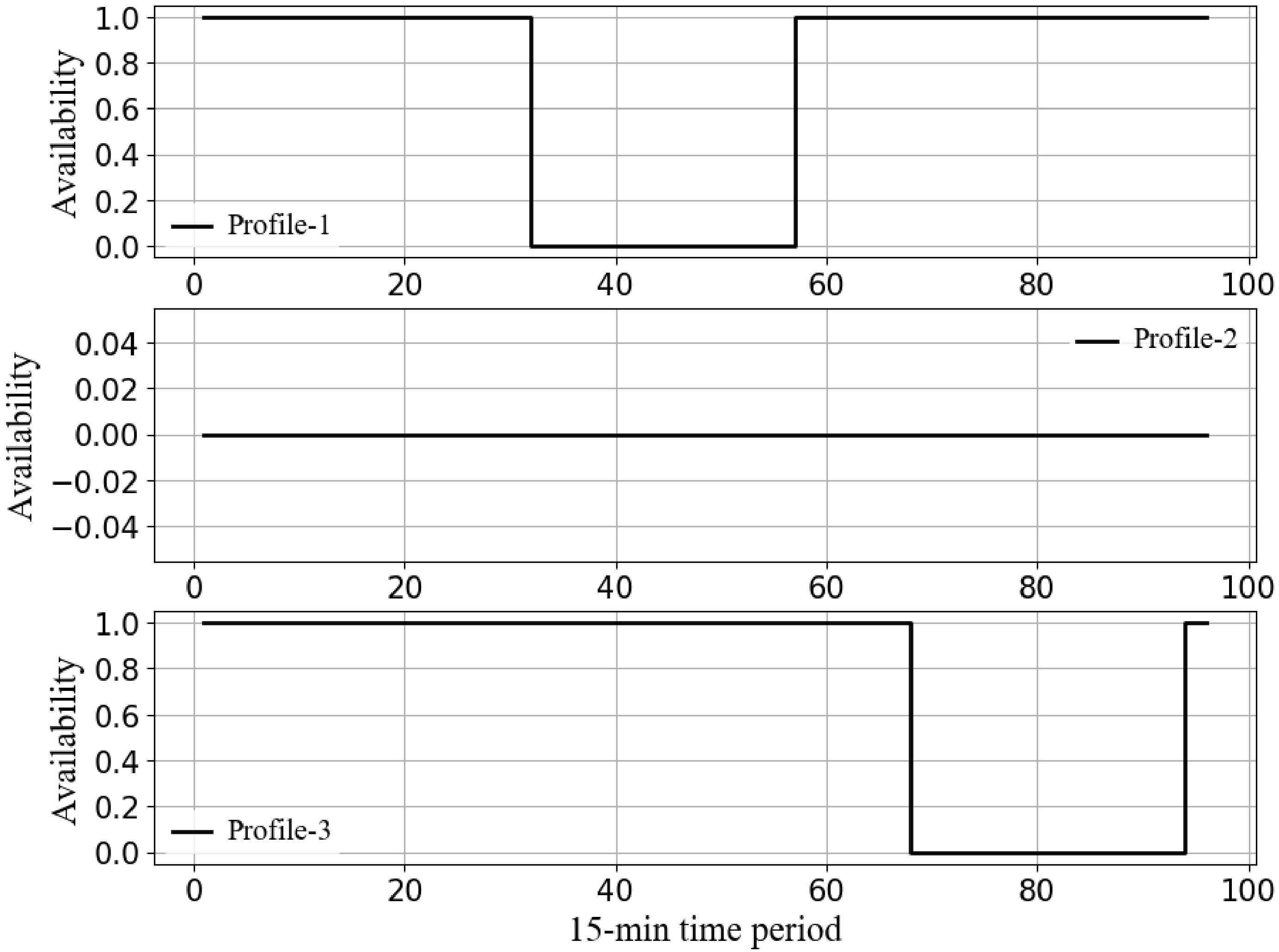
Robust Formulation

$$\underline{\alpha}_{v,t} = 1$$

$$\overline{\alpha}_{v,t} = 0$$



Robust Formulation



Robust Formulation

Bilevel Problem → Duality Theory → Single-Level Problem

$$
\begin{aligned}
&\xi_v^{wc} \geq \sum_{t \in \mathcal{T}} \widehat{\xi}_{v,t}, \quad \forall v \in \mathcal{V} \\
&\xi_v^{wc} = \min_{\alpha_{v,t}} \Big\{ \sum_{t \in \mathcal{T}} \Delta t \, \eta_v c_{v,t} \alpha_{v,t} \\
&\qquad \sum_{t \in \mathcal{T}} \alpha_{v,t} \geq K_v : (\zeta_v) \\
&\qquad \underline{\alpha}_{v,t} \leq \alpha_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}_{v,t}, \overline{\beta}_{v,t}), \quad \forall t \in \mathcal{T} \\
&\qquad \Big\}, \forall v \in \mathcal{V} \\
&\alpha_{v,t} \in \{ 0, 1 \}, \quad \forall t \in \mathcal{T}, v \in \mathcal{V}
\end{aligned}
$$

→ Non-Convex

Robust Formulation

- Constraint matrix is totally unimodular.
- Parameters (K_v, $\overline{\alpha}_{v,t}$, $\underline{\alpha}_{v,t}$) are integer.
- Under these conditions, variables take integer values.

$$\xi_v^{wc} \geq \sum_{t \in \mathcal{T}} \widehat{\xi}_{v,t}, \quad \forall v \in \mathcal{V}$$

$$\xi_v^{wc} = \min_{\alpha_{v,t}} \Big\{ \sum_{t \in \mathcal{T}} \Delta t \, \eta_v c_{v,t} \alpha_{v,t}$$

$$\sum_{t \in \mathcal{T}} \alpha_{v,t} \geq K_v : (\zeta_v)$$

$$\underline{\alpha}_{v,t} \leq \alpha_{v,t} \leq \overline{\alpha}_{v,t} : (\underline{\beta}_{v,t}, \overline{\beta}_{v,t}), \quad \forall t \in \mathcal{T}$$

$$\Big\}, \forall v \in \mathcal{V},$$

Robust Formulation

- Lower-level problem is a linear problem.
- Original bilevel problem is transformed into an equivalent single level problem by using duality theory linear programming.

$$\min_{\alpha_{v,t}} \quad \sum_{t\in\mathcal{T}} \Delta t\, \eta_v c_{v,t} \alpha_{v,t}$$

subject to:

$$\sum_{t\in\mathcal{T}} \alpha_{v,t} \ge K_v : (\zeta_v)$$

$$\underline{\alpha}_{v,t} \le \alpha_{v,t} \le \overline{\alpha}_{v,t} : (\underline{\beta}_{v,t}, \overline{\beta}_{v,t}), \quad \forall t \in \mathcal{T}$$

DUAL

$$\max_{\zeta_v, \underline{\beta}_{v,t}, \overline{\beta}_{v,t}} \quad K_v \zeta_v + \sum_{t\in\mathcal{T}} \left(\underline{\alpha}_{v,t} \underline{\beta}_{v,t} + \overline{\alpha}_{v,t} \overline{\beta}_{v,t} \right)$$

subject to:

$$\zeta_v + \underline{\beta}_{v,t} + \overline{\beta}_{v,t} \le \Delta t\, \eta_v c_{v,t} \alpha_{v,t}, \quad \forall t \in \mathcal{T}$$

$$\underline{\beta}_{v,t} \ge 0, \overline{\beta}_{v,t} \le 0, \quad \forall t \in \mathcal{T}$$

$$\zeta_v \ge 0.$$

Robust Formulation

- Single-level equivalent problem is formulated as:

Upper-Level Problem

Primal Lower Level Feasibility Constraint

Dual Lower Level Feasibility Constraint

Strong Duality

Linearization

$$\min_{\Xi^{RB}} \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} \lambda_t c_{v,t}\Delta t + \sum_{v\in\mathcal{V}}\sum_{t\in\mathcal{T}} P\left(s^+_{v,t}+s^-_{v,t}\right)$$

subject to:

$$e_{v,t} = e_{v,t-1} + \Delta t \eta_v z_{v,t} - \widehat{\xi}_{v,t} + s^+_{v,t} - s^-_{v,t}, \quad \forall t\in\mathcal{T}, v\in\mathcal{V}$$

$$c_{v,t} \le \overline{C}_v, \quad \forall v\in\mathcal{V}, t\in\mathcal{T}$$

$$\underline{E}_v \le e_{v,t} \le \overline{E}_v, \quad \forall v\in\mathcal{V}, t\in\mathcal{T}$$

$$e_{v,N_T} = e_{v,0}, \quad \forall v\in\mathcal{V}$$

$$c_{v,t}, s^+_{v,t}, s^-_{v,t} \ge 0, \quad \forall v\in\mathcal{V}, t\in\mathcal{T}$$

$$K_v\zeta_v + \sum_{t\in\mathcal{T}}\left(\underline{\alpha}_{v,t}\underline{\beta}_{v,t} + \overline{\alpha}_{v,t}\overline{\beta}_{v,t}\right) \ge \sum_{t\in\mathcal{T}}\widehat{\xi}_{v,t}, \quad \forall v\in\mathcal{V}$$

$$\sum_{t\in\mathcal{T}}\alpha_{v,t} \ge K_v, \quad \forall v\in\mathcal{V}$$

$$\underline{\alpha}_{v,t} \le \alpha_{v,t} \le \overline{\alpha}_{v,t}, \quad \forall t\in\mathcal{T}, v\in\mathcal{V}$$

$$\zeta_v + \underline{\beta}_{v,t} + \overline{\beta}_{v,t} \le \Delta t\eta_v c_{v,t}\alpha_{v,t}, \quad \forall t\in\mathcal{T}, v\in\mathcal{V}$$

$$K_v\zeta_v + \sum_{t\in\mathcal{T}}\left(\underline{\alpha}_{v,t}\underline{\beta}_{v,t} + \overline{\alpha}_{v,t}\overline{\beta}_{v,t}\right) = \sum_{t\in\mathcal{T}}\Delta t\eta_v z_{v,t}, \quad \forall v\in\mathcal{V}$$

$$0 \le c_{v,t} - z_{v,t} \le (1-\alpha_{v,t})\overline{C}_v, \quad \forall t\in\mathcal{T}, v\in\mathcal{V}$$

$$0 \le z_{v,t} \le \alpha_{v,t}\overline{C}_v, \quad \forall t\in\mathcal{T}, v\in\mathcal{V}$$

$$\underline{\beta}_{v,t} \ge 0, \overline{\beta}_{v,t} \le 0, \quad \forall t\in\mathcal{T}, v\in\mathcal{V}$$

$$\zeta_v \ge 0, \quad \forall v\in\mathcal{V}$$

$$\alpha_{v,t} \in \{0,1\}, \quad \forall t\in\mathcal{T}, v\in\mathcal{V}$$

Case Study

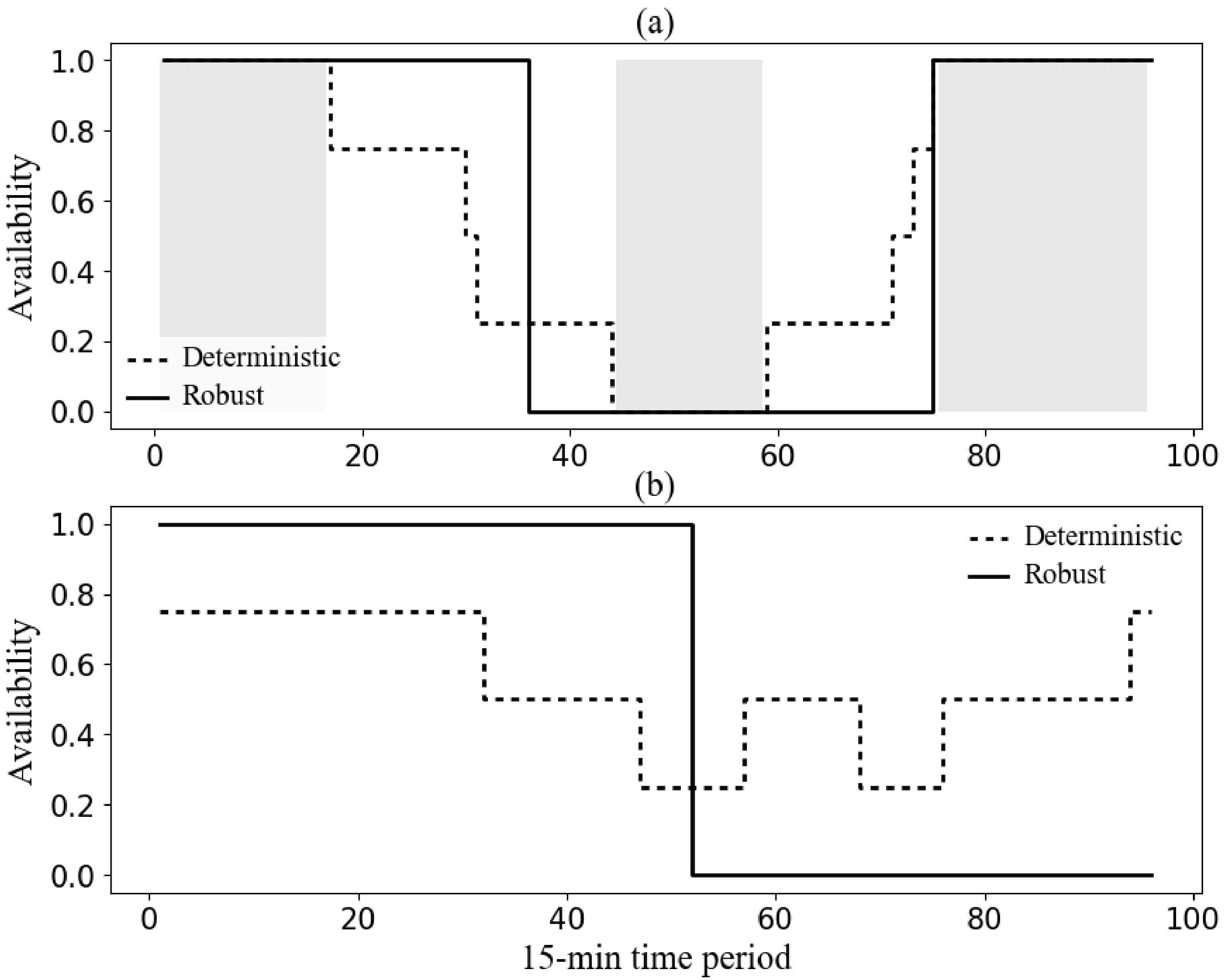
- 29 days of simulation.
- Prices from ENTSO-e Transparency Platform (2018).
- Data from National Household Travel Survey (NHTS) 2017.
- The technical parameters associated with each EV are identical (Renault ZOE)

Case Study

Day-ahead Operation of an Individual Electric Vehicle

(a) predictable pattern.

(b) non-predictable pattern.



Case Study

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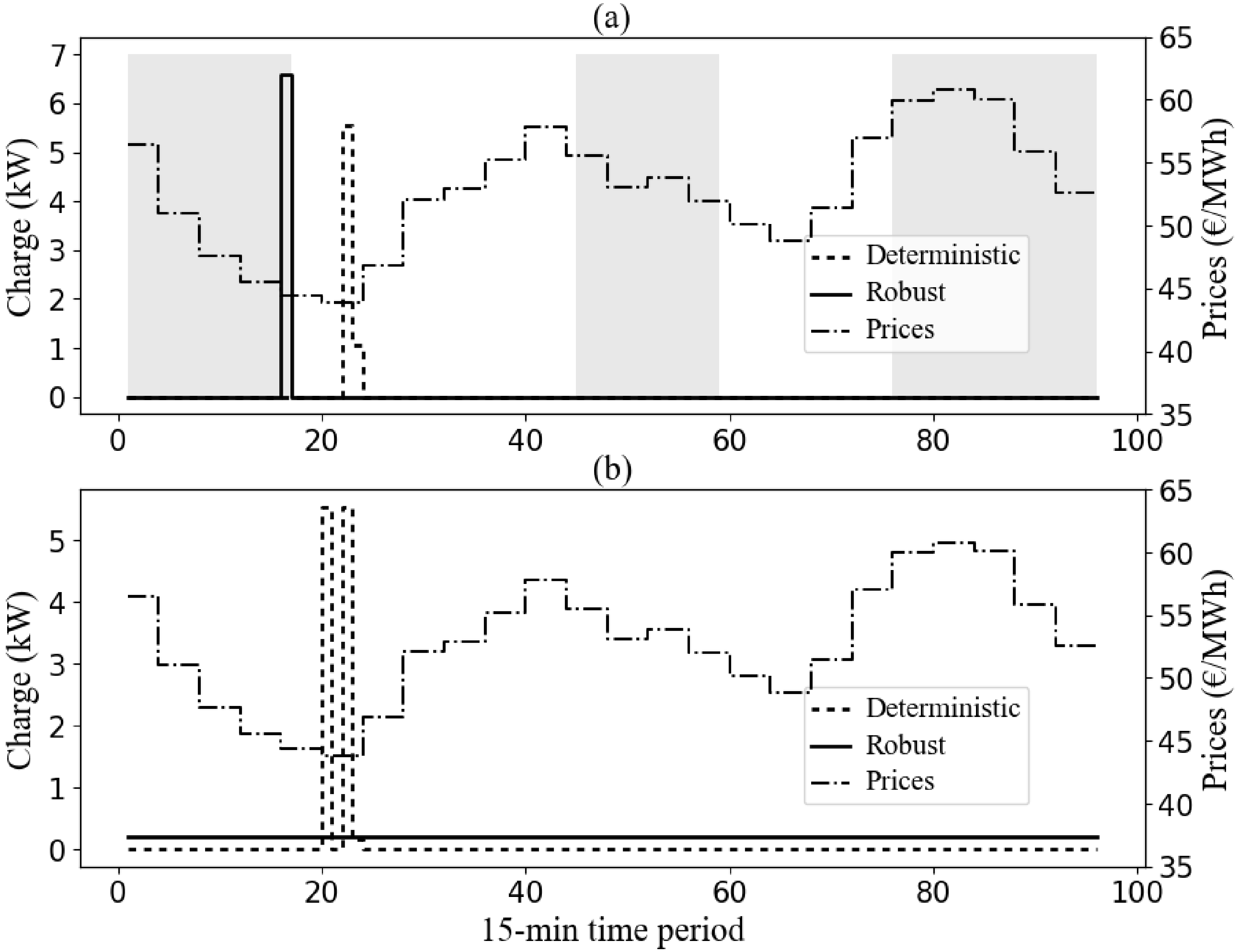

Case Study

Operation of the Fleet of Electric Vehicles

- To compare deterministic and robust optimization we solve the real-time operation of the aggregator for one month by fixing the energy bought from the day-ahead market.
- The goal of the real-time problem is to minimize the deviations from the energy balance in the EVs' batteries for the fleet of EVs.

Table 1: Results for Day 21

Metric	Deterministic	Robust
Cost in the day-ahead (€)	31.0	32.8
Purchased power in the day-ahead (kW)	1745.6	1851.2
Deviation in real time (kWh)	305.7	123.4

Case Study

Monthly Operation of the Fleet of Electric Vehicles

- RO-EV reduces the deviations up to 50% over 29 days.

Table 2: Monthly Results

Metric		**Deterministic**	**Robust**
Cost in the day-ahead (€)		586.6	643.0
Deviations in real time (kWh)	Max.	305.7	190.5
	Mean	156.9	82.9
	Min.	77.5	24.3
	Total	4548.9	2404.3

Conclusion

- A novel and computationally efficient model for the day-ahead operation of an aggregator of EVs in a residential district.

- The uncertainty on the availability of an EV is modelled via robust optimization.

- Robust approach leads to a reduction of the deviations from the energy balance of the vehicles’ batteries up to 50%.

Any questions?

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