# Multistep Electricity Price in Electricity Market in Smart Grid


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Acknowledgement: NSF CAREER Award - CNS-1350145


## Overview

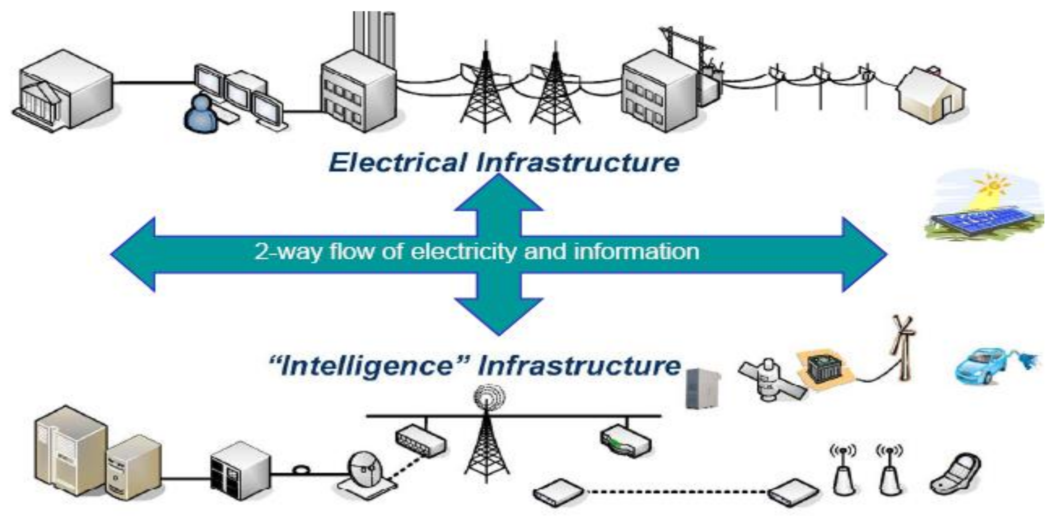


Figure 1: Smart Grid (Source: NIST)

## Problem and Our Focus

- Energy price is a critical component in power grid system operation
  - Determining optimal energy price to stimulate consumers to promote energy saving and achieve load balancing and fairness in electricity consumption
- Our research focuses on
  - Developing multistep electricity price model and determining electricity quantity and price in those steps
  - Investigating security risks of multistep electricity price model

## One-Dimensional Multistep Electricity Price (MEP) Modeling

- Objective
  - To make the electricity consumption from users with less charge

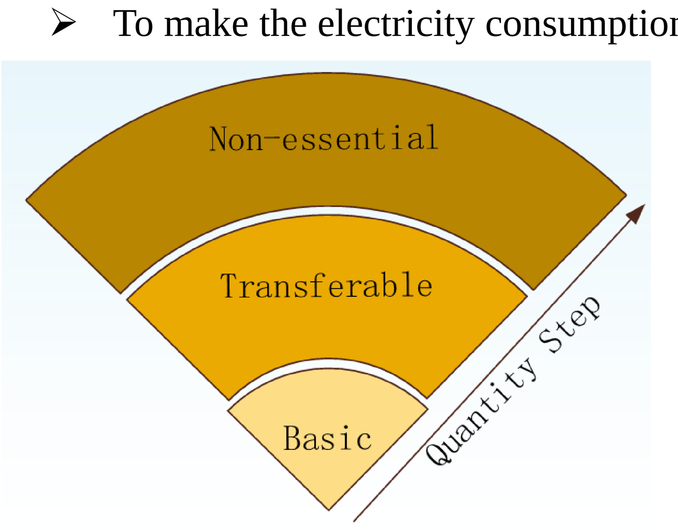


Figure 2: One Dimensional MEP Model

- Quantity Increase
- Demand/Supply Balance
- Economic Balance
- Minimum Cost
- Price Different

$$Objective.\quad \begin{cases} Max\{\alpha\} \\ Max\{\beta\} \end{cases}$$

$S.t.$

$$load = load^b + load^t + load^n$$

$$\begin{cases} load = \frac{10}{\alpha} load^b = \frac{10}{\beta} load^t = \frac{10}{\lambda} load^n \\ \alpha + \beta + \lambda = 10 \end{cases}$$

$$\begin{cases} \alpha < \beta < \frac{G_S^{max} + G_W^{max}}{load} < \alpha + \beta \\ \alpha < \beta < \lambda \\ \alpha, \beta, \lambda \in \mathbf{Z} \end{cases}$$

$$\mathbf{p} = \begin{bmatrix} p^b \\ p^t \\ p^n \end{bmatrix} = \begin{bmatrix} Cost^b / load^b \\ Cost^t / load^t \\ Cost^n / load^n \end{bmatrix}$$

$$p^t - p^b < p^n - p^t$$

## New Two-Dimensional Multistep Electricity Price (MEP) Model

- To promote energy saving and achieve load balancing and fairness in electricity consumption
- **Two-dimensional multistep electricity price model**
  - Quantity of electricity consumption
    - Basic step
    - Transferable step
    - Non-essential step
  - Time of electricity being used
    - Off-peak step
    - Mid-peak step
    - On-peak step

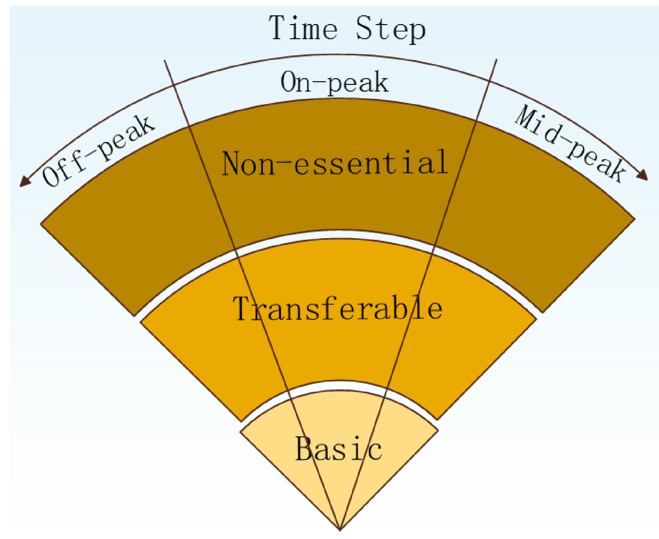


Figure 3: Two Dimensional MEP Model

- Step Increase
- Demand/Supply Balance
- Economic Balance
- Minimum Cost
- Price Difference
- Balance Load over Time

$$Objective.\quad \begin{cases} Max\{\alpha\} \\ Max\{\beta\} \end{cases}$$

$S.t.$

$$load = load^b + load^t + load^n$$

$$\begin{cases} load = \frac{10}{\alpha} load^b = \frac{10}{\beta} load^t = \frac{10}{\gamma} load^n \\ \alpha + \beta + \gamma = 10 \end{cases}$$

$$\begin{cases} \alpha < \beta < \frac{G_S^{max} + G_W^{max}}{load} < \alpha + \beta \\ \alpha < \beta < \gamma \\ \alpha, \beta, \gamma \in \mathbb{Z} \end{cases}$$

$$\begin{cases} load^b = load^b(l) + load^b(m) + load^b(h) \\ load^t = load^t(l) + load^t(m) + load^t(h) \\ load^b = load^n(l) + load^n(m) + load^n(h) \end{cases}$$

$$\begin{cases} load^b(l) < load^t(l) < load^n(l) \\ load^b(m) < load^t(m) < load^n(m) \\ load^b(h) < load^t(h) < load^n(h) \end{cases}$$

$$\sum_{x \in \{m,l,h\}} \Big( \sum_{y \in \{b,t,n\}} load^y(x) - \frac{1}{3} load \Big)^2 \le \phi$$

$$p = \begin{bmatrix} \frac{Cost^b(l)}{load^b(l)} & \frac{Cost^b(m)}{load^b(m)} & \frac{Cost^b(h)}{load^b(h)} \\ \frac{Cost^t(l)}{load^t(l)} & \frac{Cost^t(m)}{load^t(m)} & \frac{Cost^t(h)}{load^t(h)} \\ \frac{Cost^n(l)}{load^n(l)} & \frac{Cost^n(m)}{load^n(m)} & \frac{Cost^n(h)}{load^b(h)} \end{bmatrix}$$

$$p^t - \quad p^b < \quad p^n - \quad p^t$$

## Data Integrity Attacks

- The adversary could inject false measurement reports to disrupt the smart grid operations through compromised meters and sensors
- Those attacks denoted as data integrity attacks
- We investigate the risk and impact of data integrity attacks against the electricity market operations (i.e., multistep electricity price)

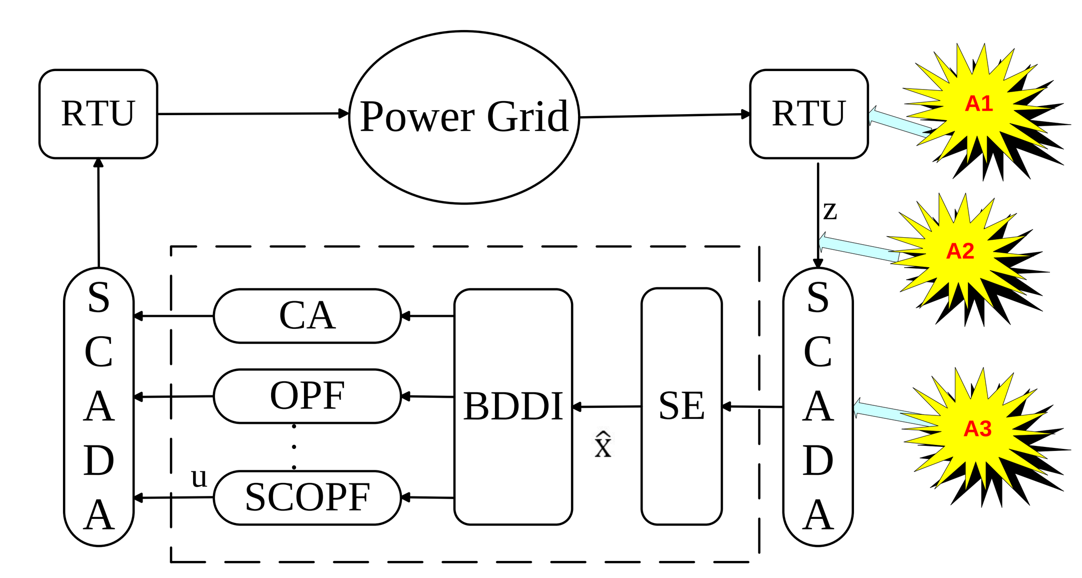


Figure 4: Data Integrity Attacks against Smart Grid Operations

## Security Scenarios and Analysis

ATTACK CASES

| | |
|---|---|
| Case A: | $\sum Gen_j < \sum load_i < \sum load_i^* \le load^b$ |
| Case B : | $\sum load_i < load^b < \sum load_i^* \le load^t$ |
| Case C : | $\sum load_i < load^b < load^t < \sum load_i^*$ |
| Case D : | $load^b < \sum load_i < \sum load_i^* \le load^t$ |
| Case E : | $load^b < \sum load_i < load^t < \sum load_i^*$ |
| Case F : | $load^t < \sum load_i < \sum load_i^*$ |

PRICE CHANGE IN ATTACK CASES

| | | | |
|---|---|---|---|
| Case A: | $\begin{cases} p^{*b} - p^b = 0 \\ p^{*t} - p^t > 0 \\ p^{*n} - p^n = 0 \end{cases}$ | Case B : | $\begin{cases} p^{*b} - p^b = 0 \\ p^{*t} - p^t > 0 \\ p^{*n} - p^n = 0 \end{cases}$ |
| Case C : | $\begin{cases} p^{*b} - p^b = 0 \\ p^{*t} - p^t > 0 \\ p^{*n} - p^n = 0 \end{cases}$ | Case D : | $\begin{cases} p^{*b} - p^b = 0 \\ p^{*t} - p^t > 0 \\ p^{*n} - p^n = 0 \end{cases}$ |
| Case E : | $\begin{cases} p^{*b} - p^b = 0 \\ p^{*t} - p^t > 0 \\ p^{*n} - p^n = 0 \end{cases}$ | Case F : | $\begin{cases} p^{*b} - p^b = 0 \\ p^{*t} - p^t = 0 \\ p^{*n} - p^n = 0 \end{cases}$ |

## Evaluation Results

- Simulation Setup
  - IEEE 9-bus system
  - Parameters

GENERATOR PARAMETERS OF IEEE 9-BUS SYSTEM

| Unit Type | Marginal Cost | Maximum Generation |
|---|---|---|
| Bulk | 50$/MWh | 620MW |
| Wind | 10$/MWh | 85MW |
| Solar | 10$/MWh | 67MW |

ELECTRICITY CONSUMPTION ON NORMAL AND ATTACK CASE (LOAD:$MWh$)

| | User1 | User2 | User3 | User4 | User5 | User6 |
|---|---|---|---|---|---|---|
| Normal case | 10 | 90 | 30 | 100 | 125 | 155 |
| Attack Case A | ∗15 | 90 | 30 | 100 | 125 | 155 |
| Attack Case B | ∗40 | 90 | 30 | 100 | 125 | 155 |
| Attack Case C | ∗70 | 90 | 30 | 100 | 125 | 155 |
| Attack Case D | 10 | 90 | ∗40 | 100 | 125 | 155 |
| Attack Case E | 10 | 90 | ∗80 | 100 | 125 | 155 |
| Attack Case F | 10 | ∗130 | 30 | 100 | 125 | 155 |

- Simulation Results

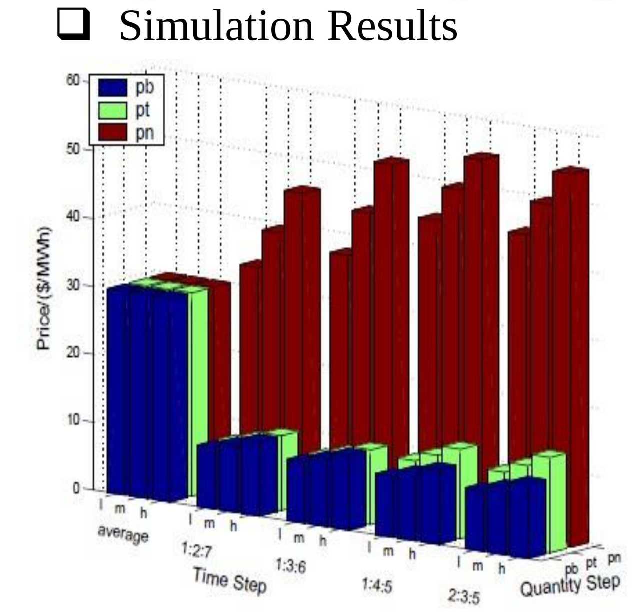


Figure 5: Electricity Consumption and Price in Steps

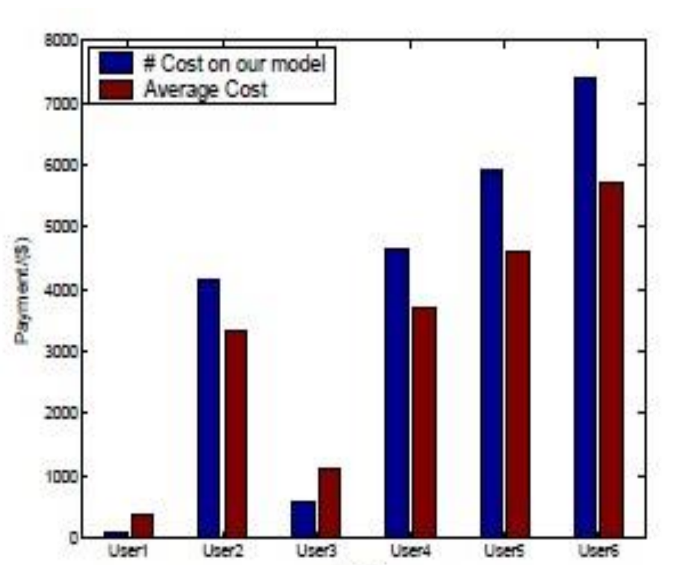
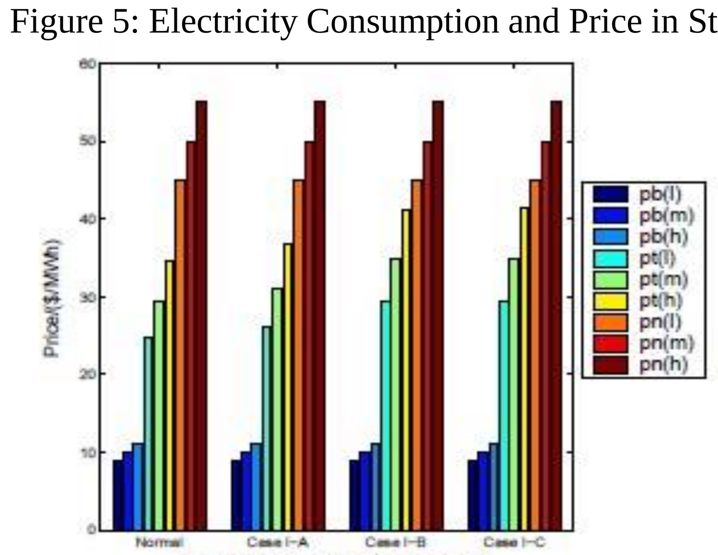


Figure 6: Payment to Each Users in MEP Model


(a)

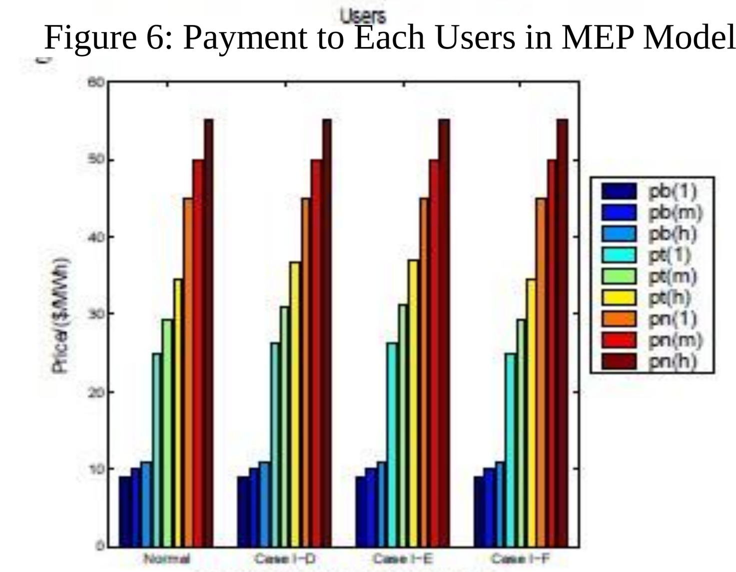

(b)

Figure 7 (a)(b): Impact of Data Integrity Attacks