Information Networks in Smart Grid

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Outline

Smart Grid: overview

Can false data lead to power blackout?

We have seen power systems everyday

- Power generation (hydropower, solar, wind power, nuclear etc)

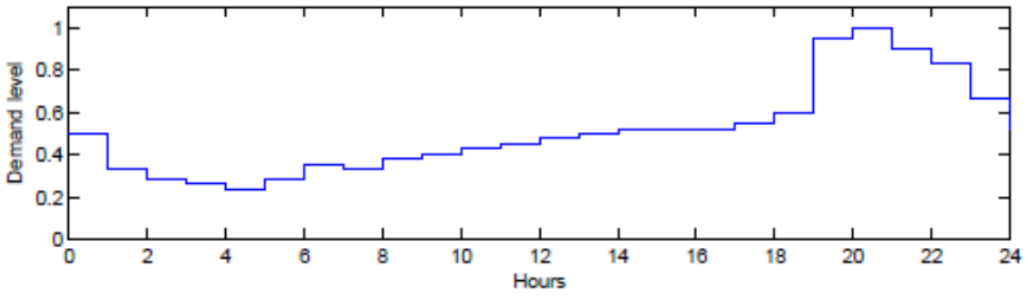
- High-voltage power transmission

- Medium voltage distribution lines

- Commercial, industrial and residential users

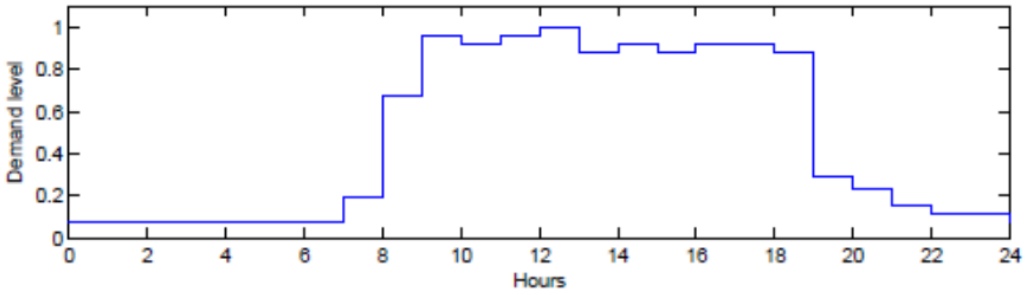
Different users have different power demand load

- Residential users



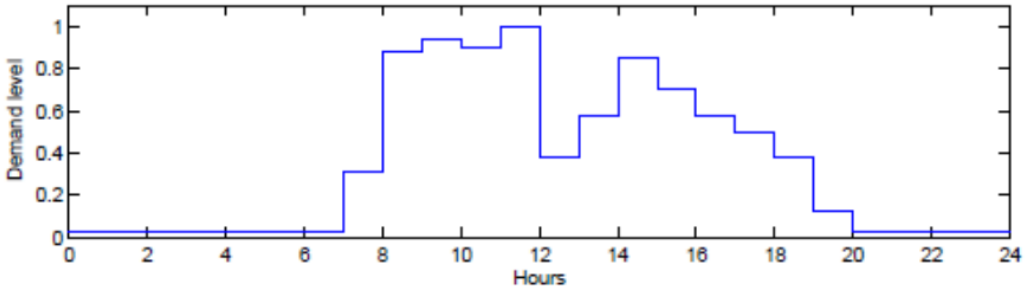
(a) Residential load.

- Commercial users



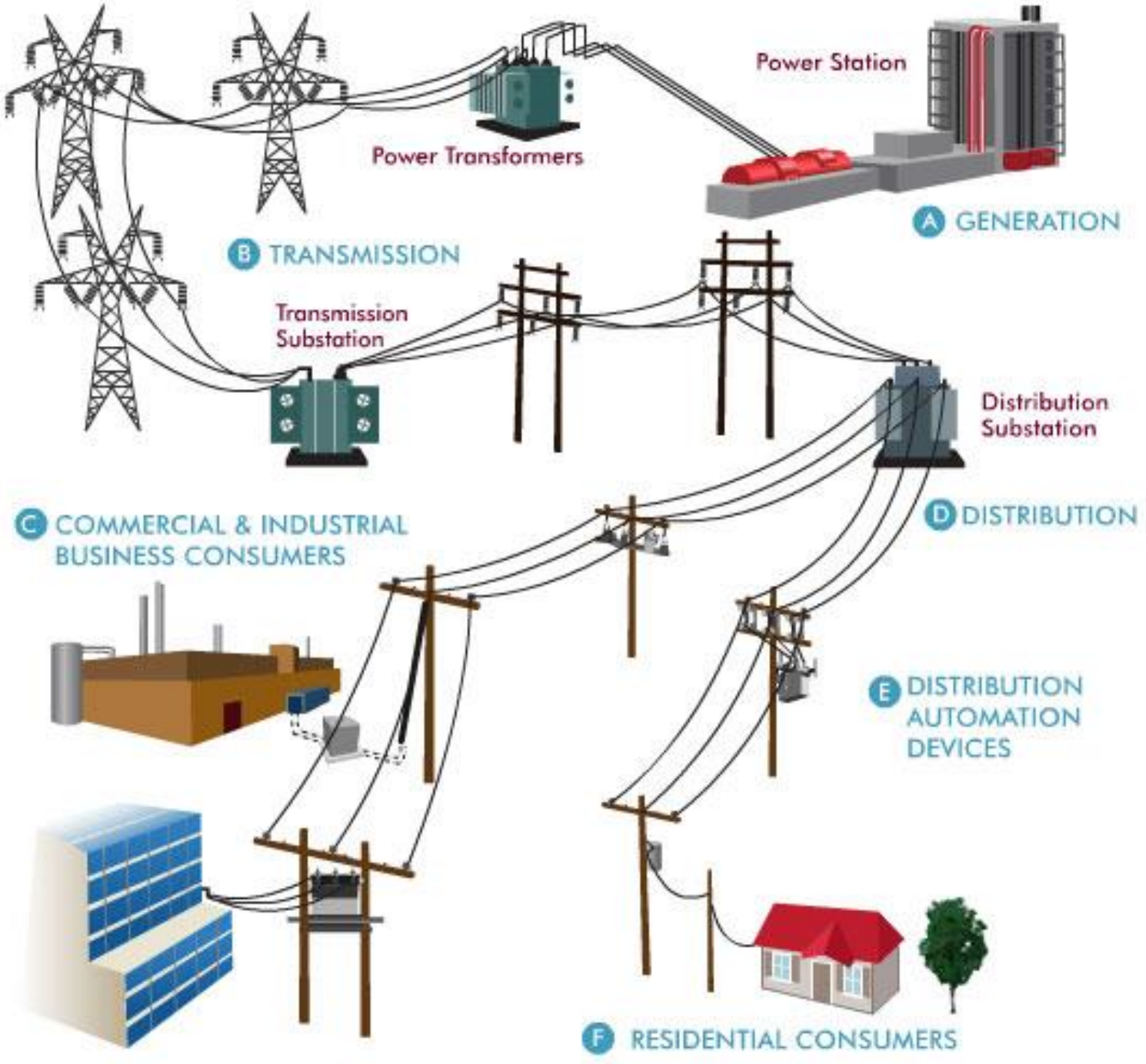
(b) Commercial load.

- Industrial users

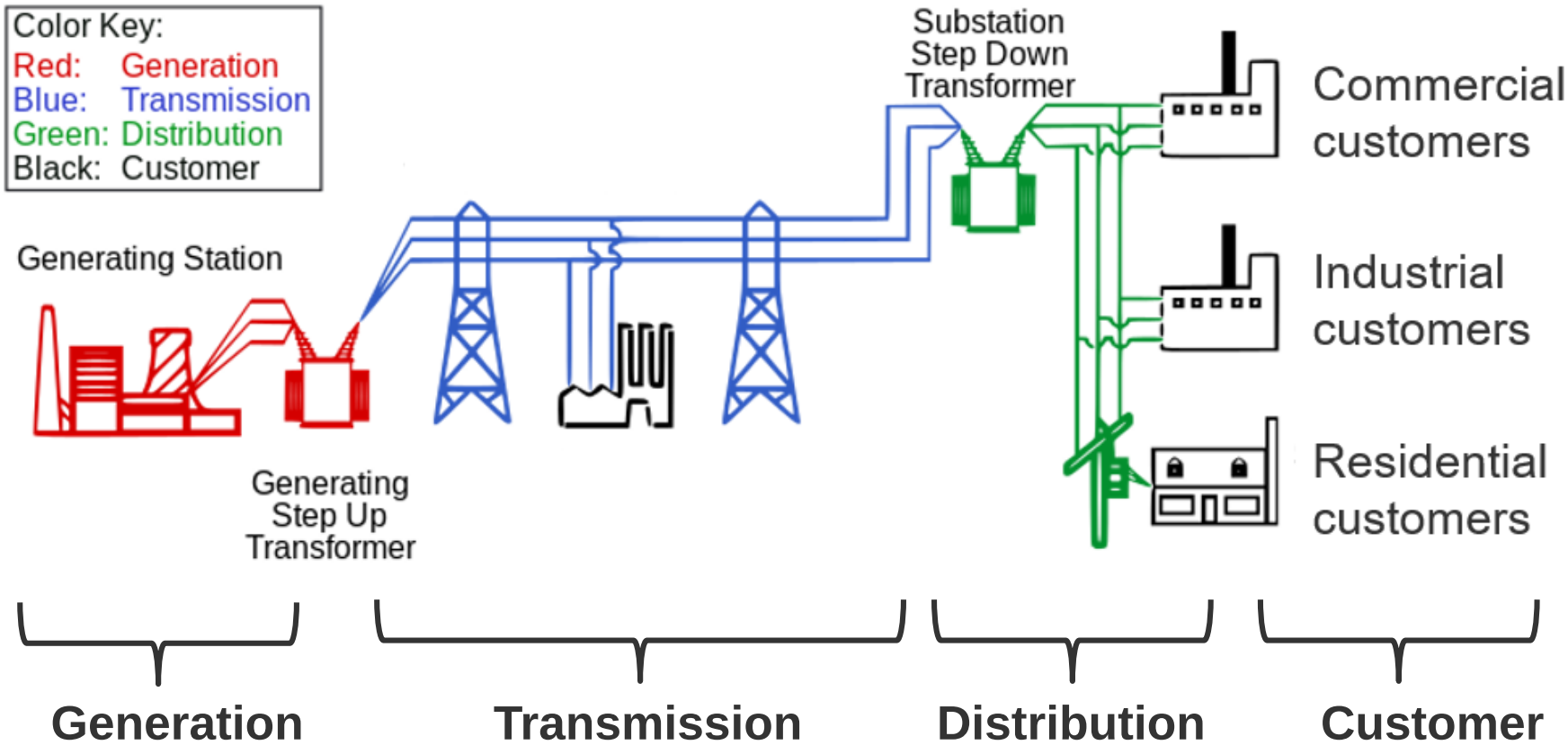


(c) Industrial load.

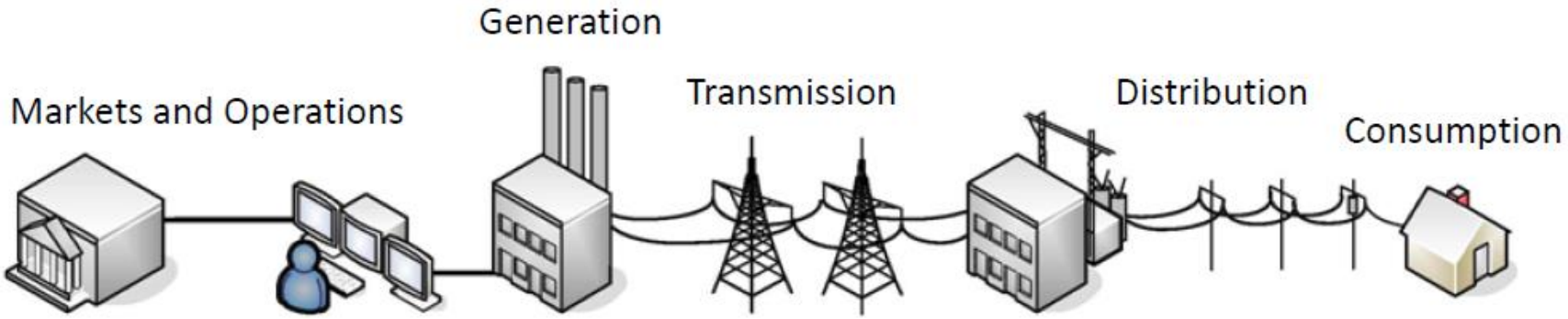
Power Grid Architecture



Power systems abstract model

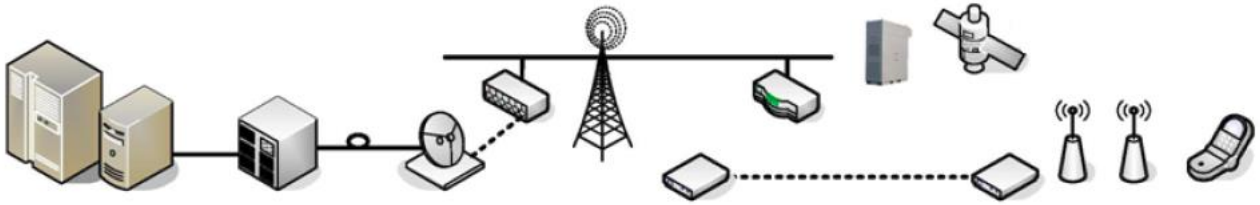


Smart Grid = Power Grid + ICT



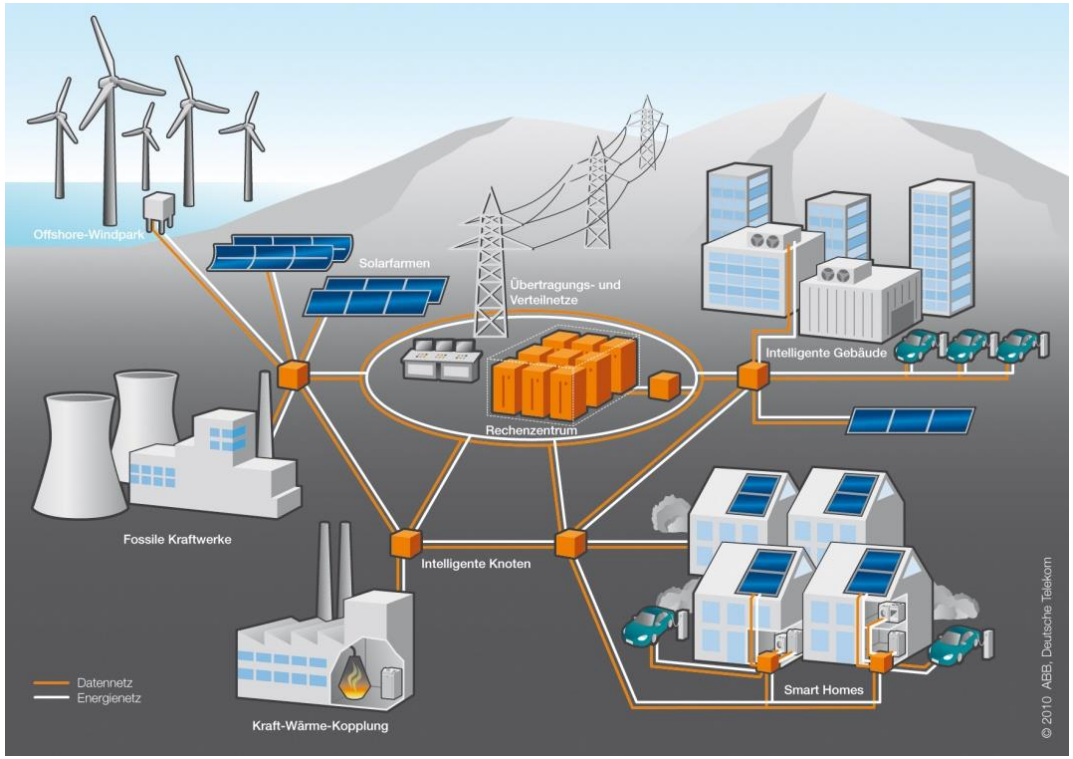
Power infrastructure

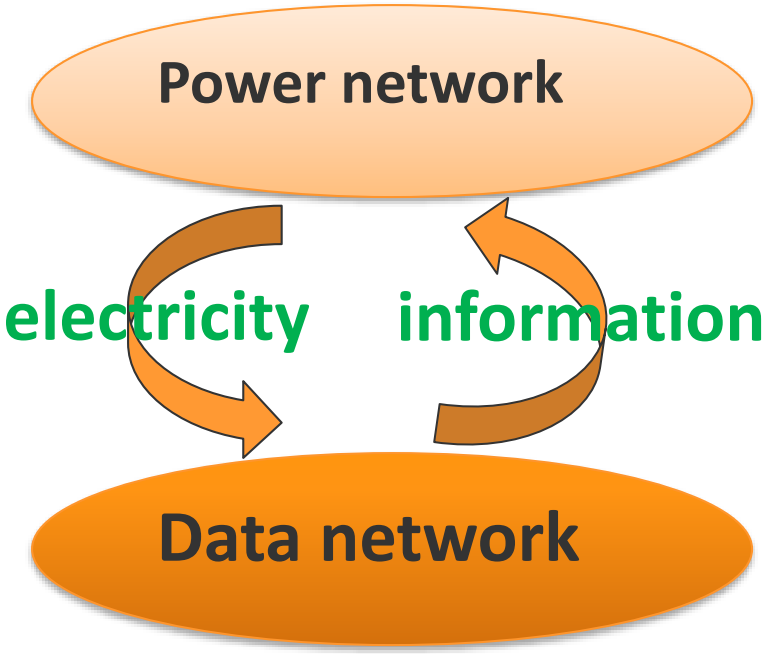
Two way flow of electricity and data



Communications infrastructure

Two parallel and interacting networks: Data network; and power network





data network

power network

Two-way Information flow needs in the smart grid

- Smart metering and Advanced Metering Infrastructure(AMI)
- Distributed generation
- Power outage detection
- Online monitoring, diagnostics and protection
- Massive amounts of sensor, telemetry, and control data
- Further analysis control, real time pricing
- Communications network support energy scheduling

Smart Meter

- Smart meters perform functions
  - energy consumption
  - communications with other intelligent devices in the home and utility
  - Time-based pricing
  - Loss of power (and restoration) notification
  - Remote turn on / turn off operations
  - Energy prepayment
  - Power quality monitoring

- Smart meters are normally organized as a network to access points

ICT Technologies for Smart Grid

Communications

- Powerline Communication; Wireless sensor networks; Wireless mesh networks; Cellular communication and networks; Cognitive radio; Machine-to-machine communications

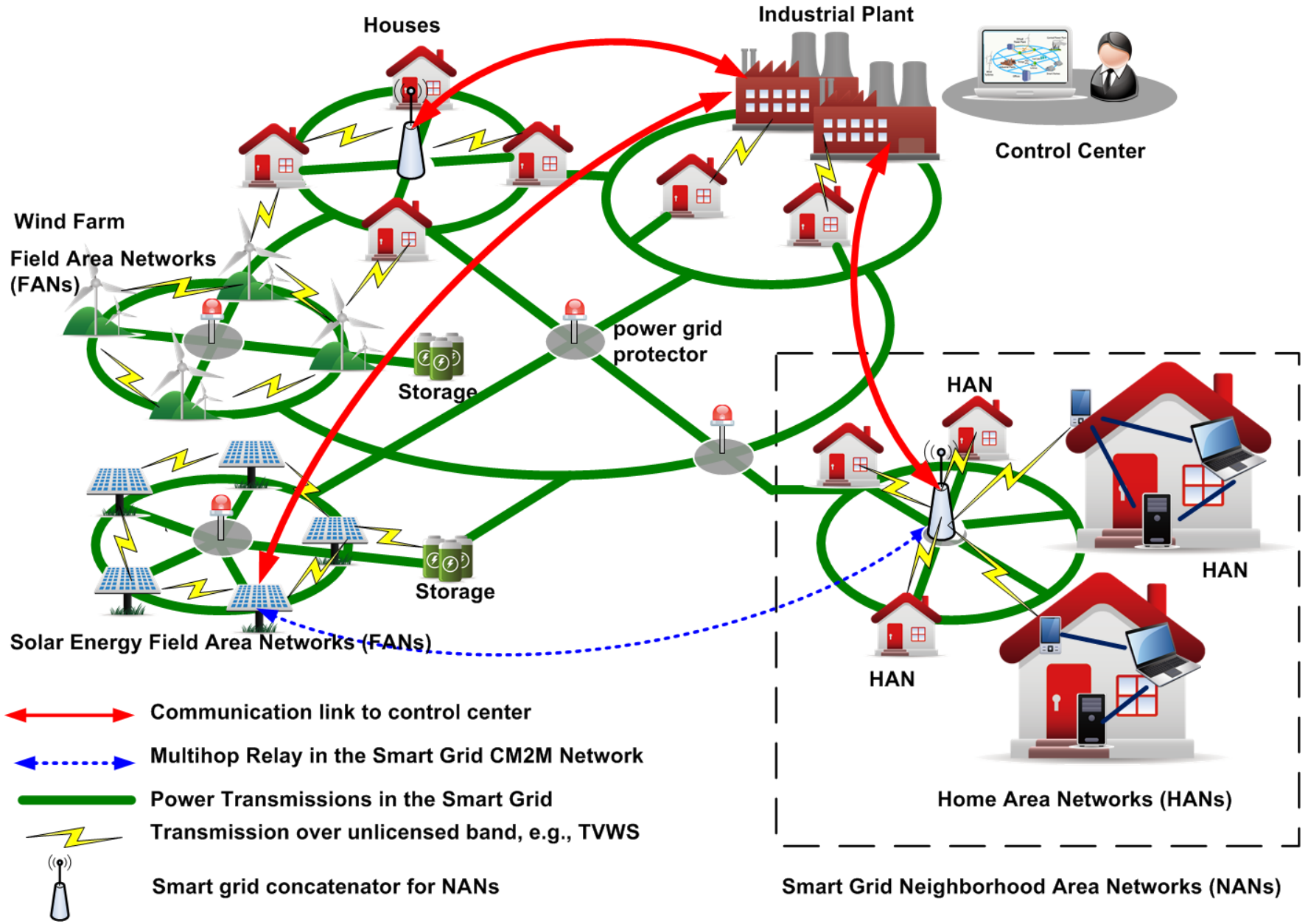
Computation

- Big data,
- Cloud computing, edge/fog computing
- Software Defined Networking (SDN)

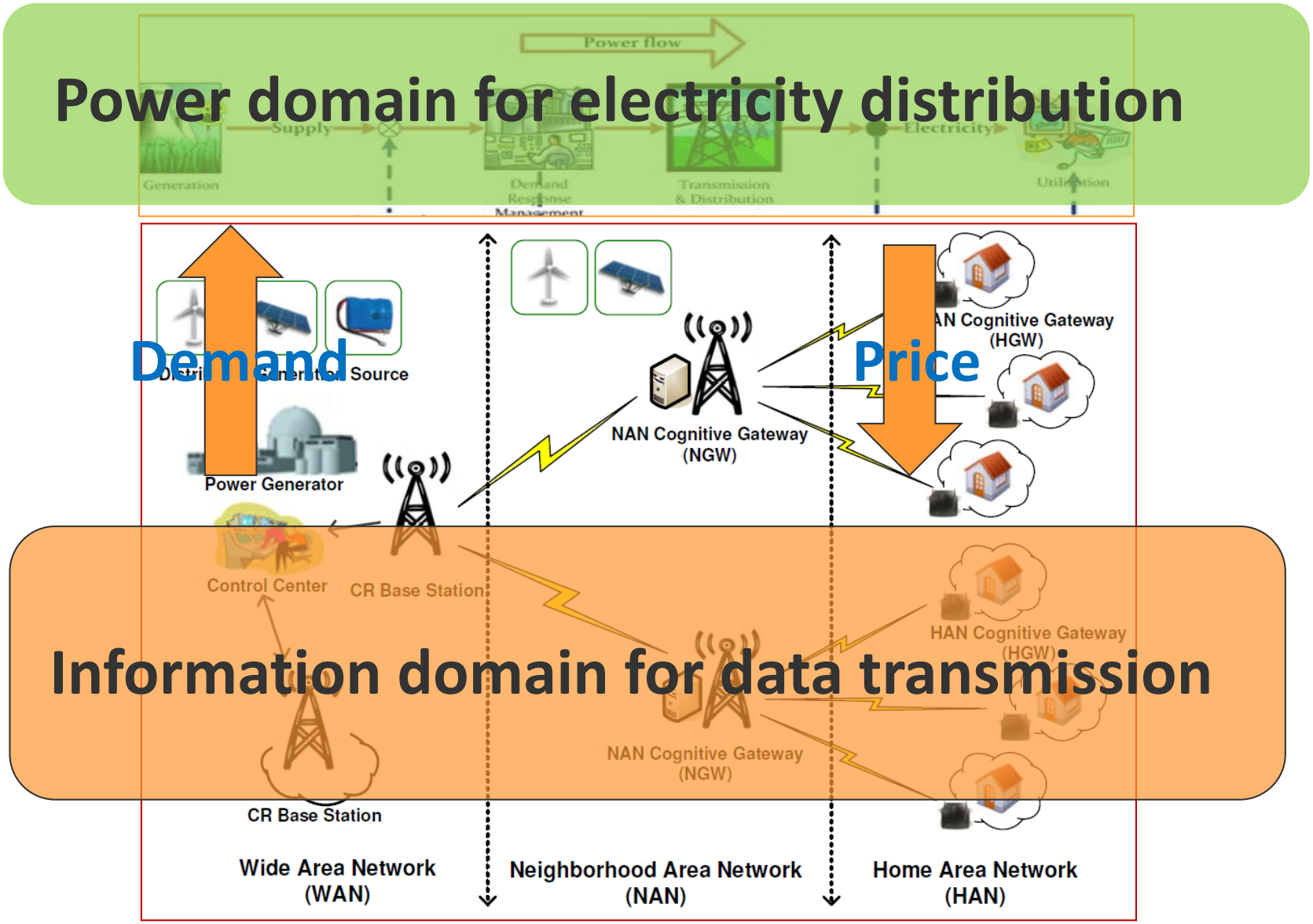
Control

- Control theory, optimization, queueing theory
- game theory (e.g., cooperative game, non-cooperative game, Stackelberg game, evolutionary game, coaliation game, auction theory, price theory, contract theory)

Smart grid communications and power distribution [Zhang et al. NetMag'12];



Information flow between information and energy domains



- 3G; 4G; 5G
- Mesh networks
- Cognitive radio
- Smart meters
- Meter-to-meter

DIVERGED DATA LEADS TO POWER BLACKOUT

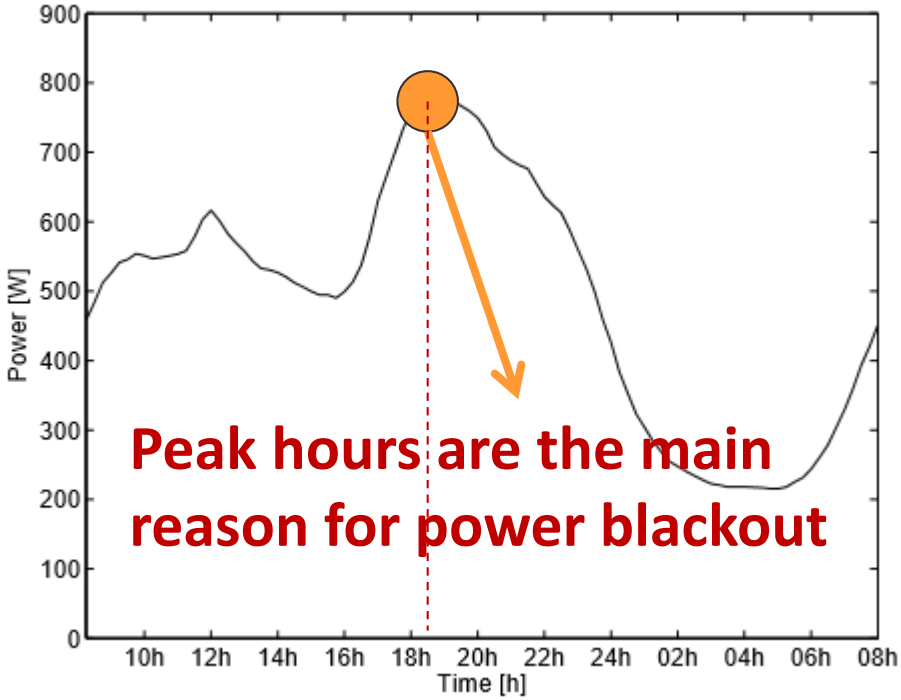
Different reasons lead to smart grid instability

- Intermittent renewable energy are time-varying and location-varying
- Large number of electric vehicles charging
- Energy storage, battery capacity
- Communications networking failure
- Simultaneous usage of power in an area, e.g, air conditioner in Summer

- Data capturing: replay attack, eavedropping
- Data deceiving: tampering, spoofing
- Data blocking: jamming
- False data injection attack

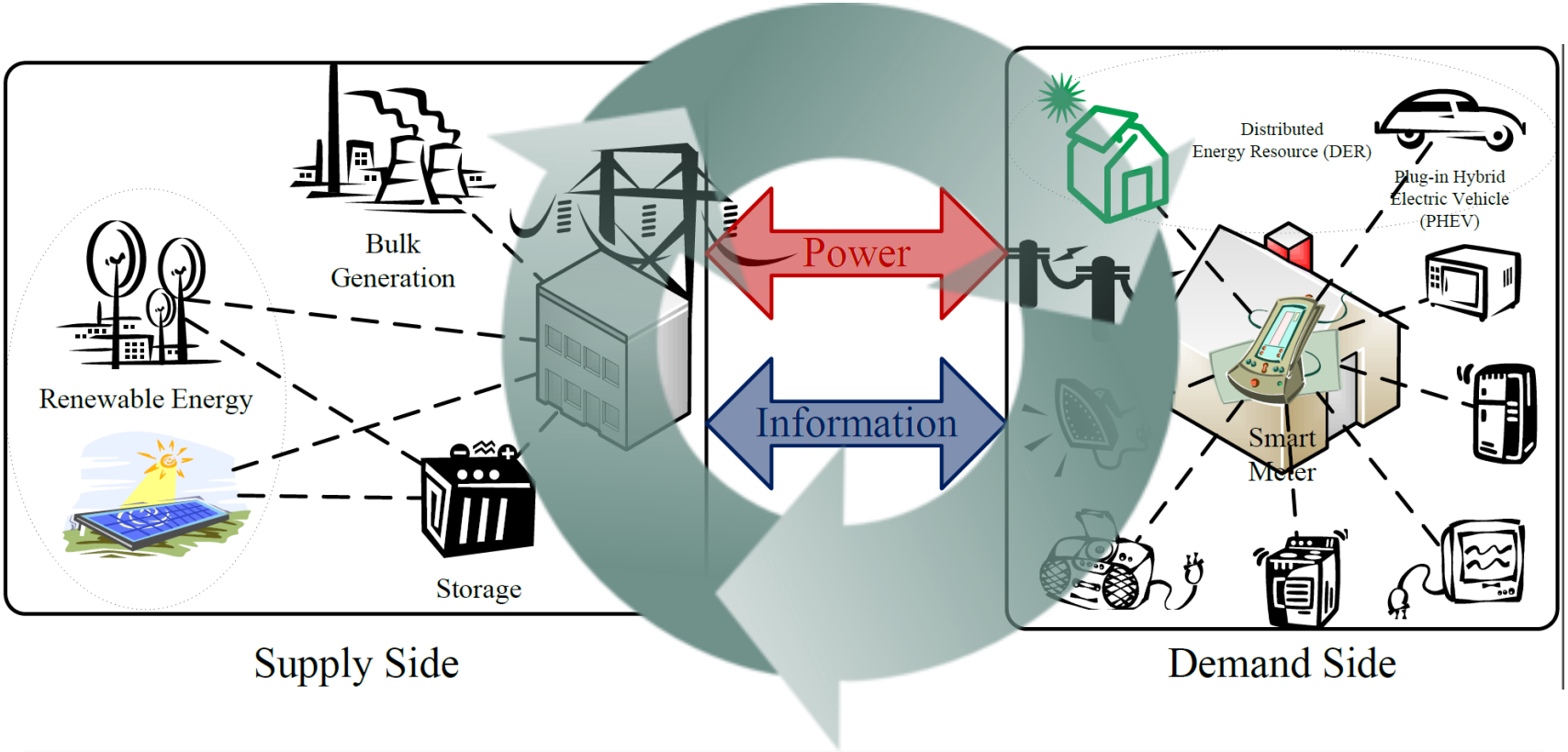
Peak load is the main reason for power blackout

- The power load may significantly vary over time and location
- The practical load profile is very unbalanced for different users
  - Residential peak load (late afternoon)
  - Industrial peak load (morning)



Household load in winter
(source: www.vreg.be)

Demand Response Management (DRM) is the main approach to flat peak load



DRM studies the interaction between the supply and the demand sides by two-way flows of power and information.

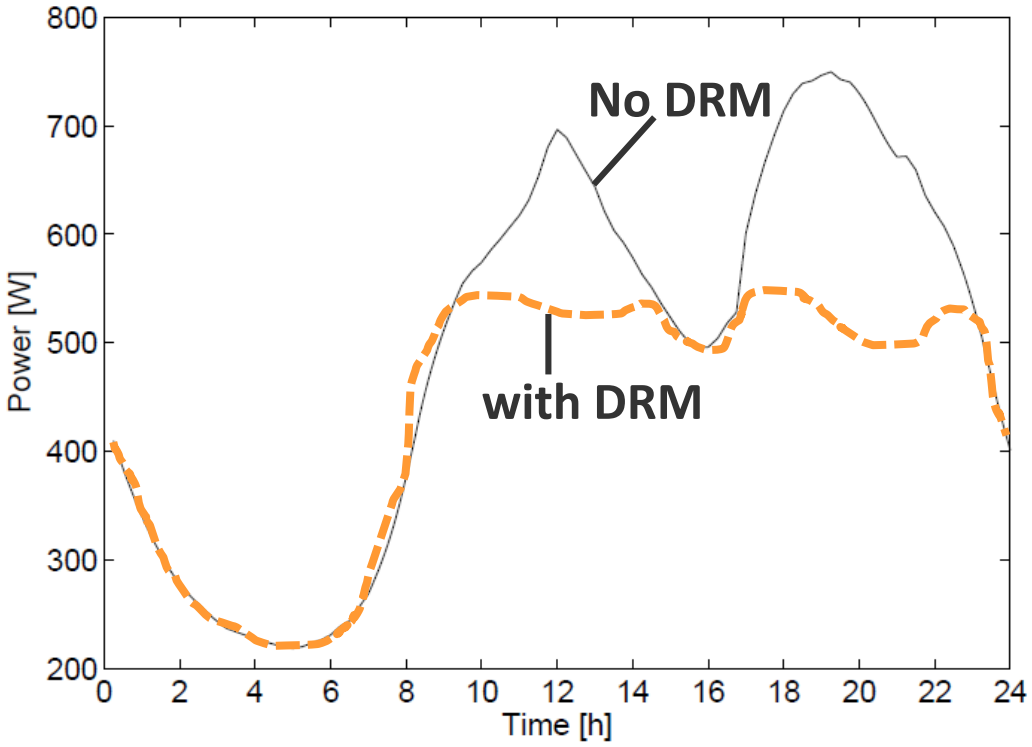
Demand Response Management (DRM) objectives

Reduce energy consumption

- encourage energy-aware consumption patterns
- Reduce power generation

Shift the energy consumption

- Mitigate power load during the peak hours
- Improve grid reliability



Demand Response Management (DRM) definition

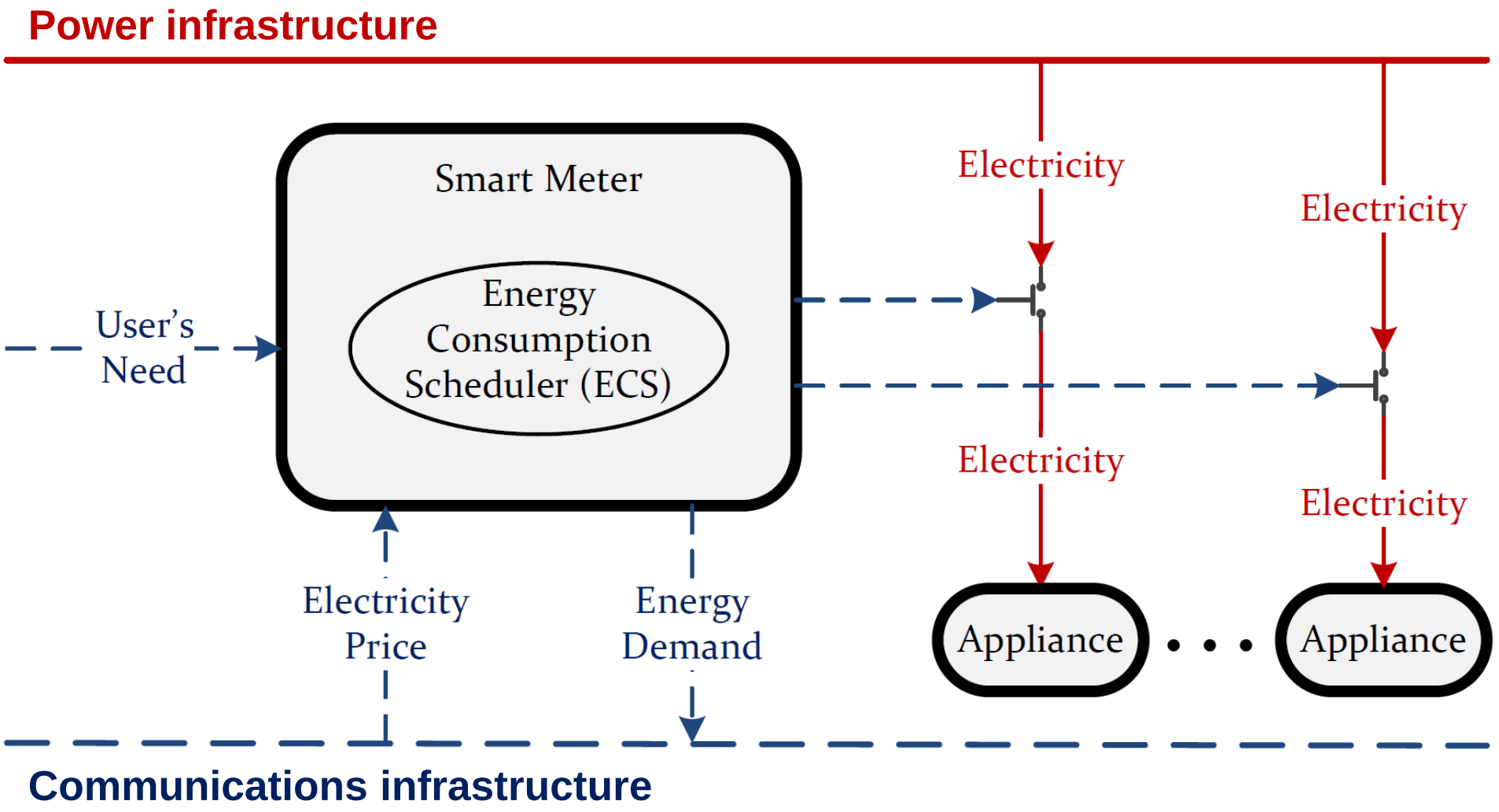
- According to the US. Department of Energy

> Demand Response Management (DRM) is defined as changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.

- In plain language
  - Users will change energy usage behaviors according to different electricity prices, or incentive payments, or system reliability

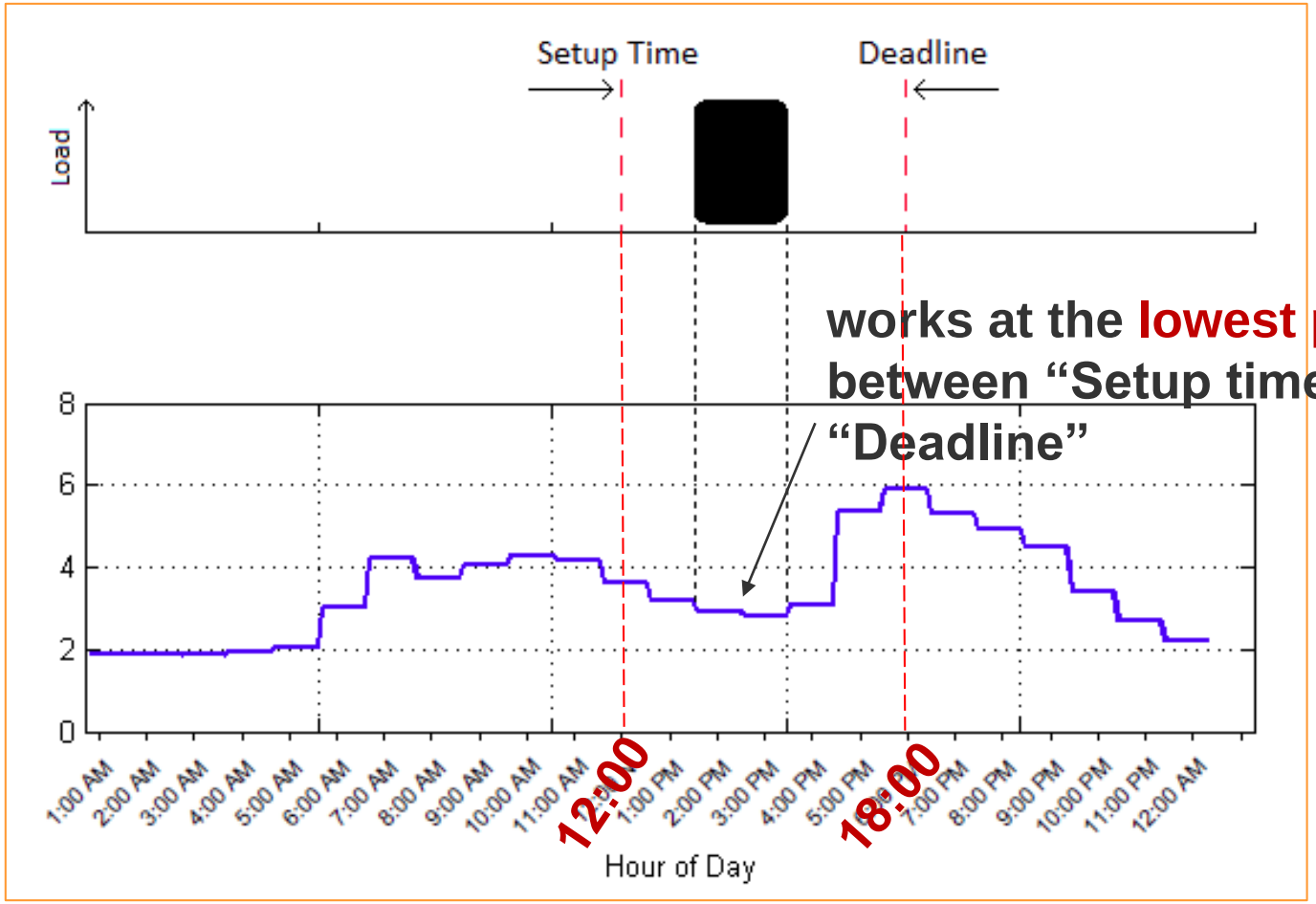
- DRM is able to help reduce peak load and increase reliability

Home Energy Management



Energy Consumption Scheduling

- A simple example: dishwasher after lunch (Q: why choose time period between 1:30-3:30pm?)



Classic energy scheduling problem

- **Energy Consumption Scheduling problem to minimize cost:**

$$\min_{\boldsymbol{x}} \sum_{h=1}^{H} p^h \times \left(\sum_{a \in A} x_a^h \right)$$

Load from all appliances in hour *h*

Subject to

$$\sum_{h=\alpha_a}^{\beta_a} x_a^h = E_a, \qquad \forall a \in A,$$

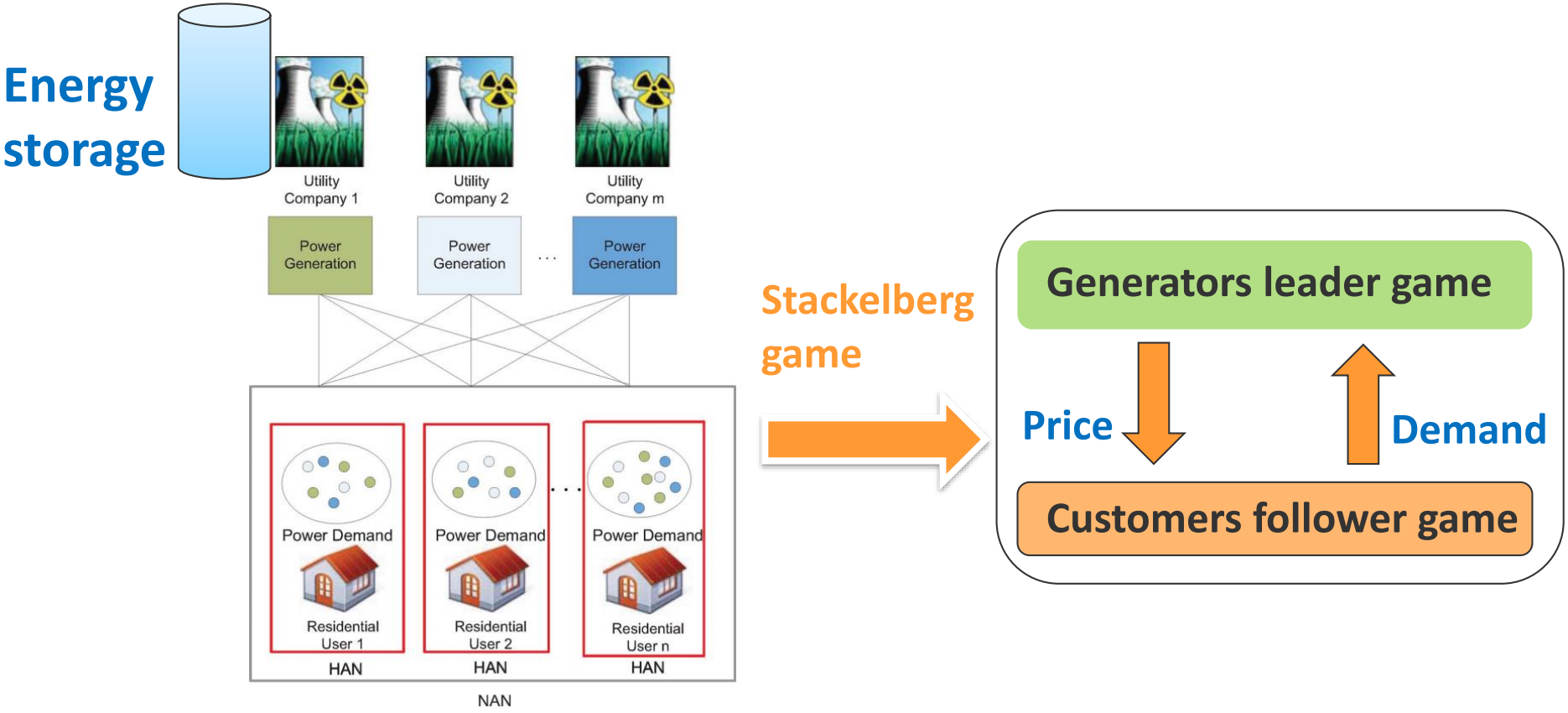
$$\gamma_n^{\min} \le x_a^h \le \gamma_n^{\max}, \qquad \forall a \in A, h \in [\alpha_a, \beta_a]$$

$$x_a^h = 0, \qquad \forall a \in A, h \notin [\alpha_a, \beta_a]$$

  - **where p^h denote the price of electricity at hour *h*. Could be ToU or RTP model**

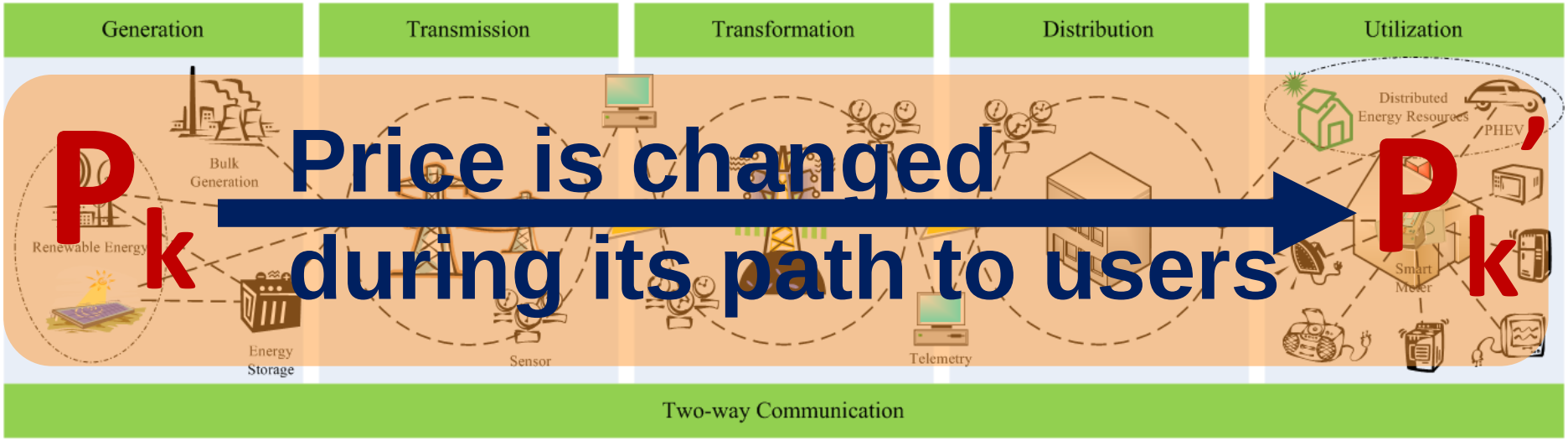
- **This is a linear programming optimization problem**

Reliable Smart Energy Networks with Energy Storage [w/ Sabita et al. TSG'13] → ESI "Highly Cited Paper"



- Distributed and centralized energy storage
- Energy storage increases dependability

Attack on price information and its physical damage impact



P_k **Price is changed during its path to users** **P_k'**

False or diverged price :

- Cyber attack with false price information injection or manipulation
- Overloaded power networks; Equipment damage

Consequence:

- New price leads to new power demand from users

False price and its physical damage impact

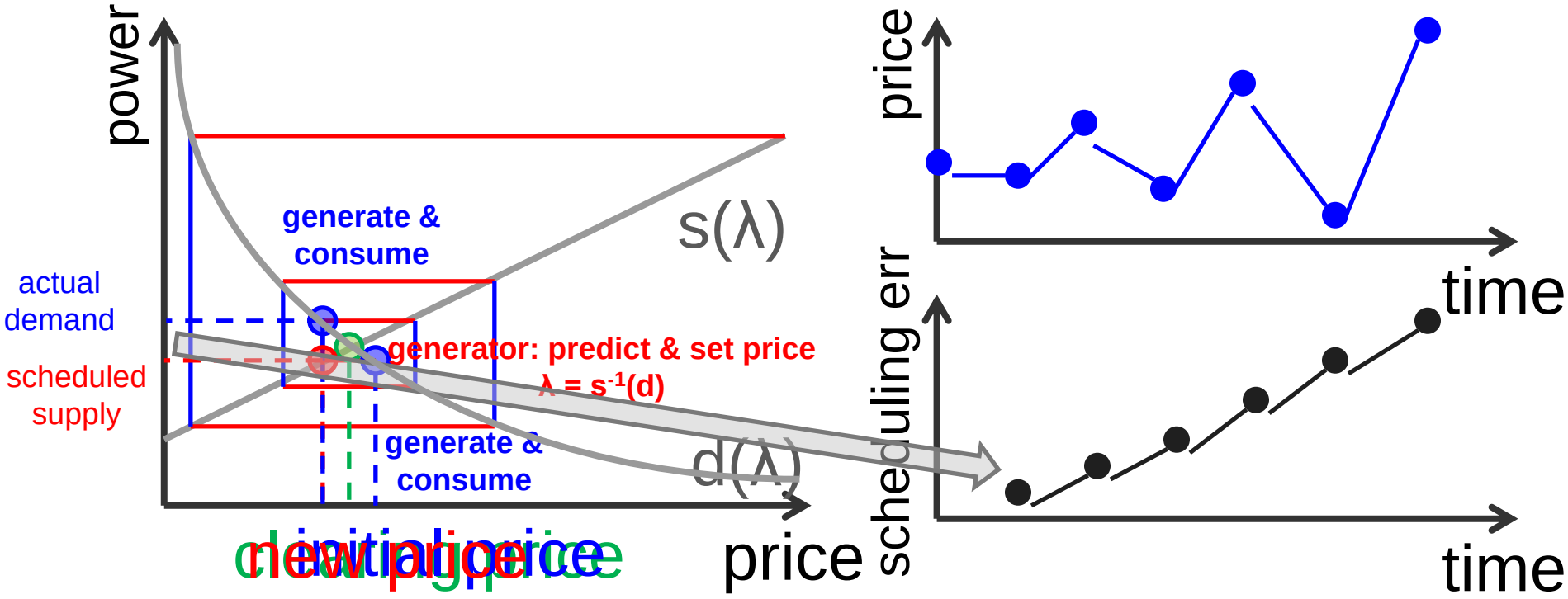
Attack: **manipulating price**

- $p_k' = p_k + \delta_k$: **new price after attack**
- x_k': **new power demand**

- **If $p_k' < p_k$: false price is lower than the original price.**
- **then, $x_k' > x_k$**
  - **Higher demand than the generated power from the generators**
  - **hence grid instability and possible blackout**

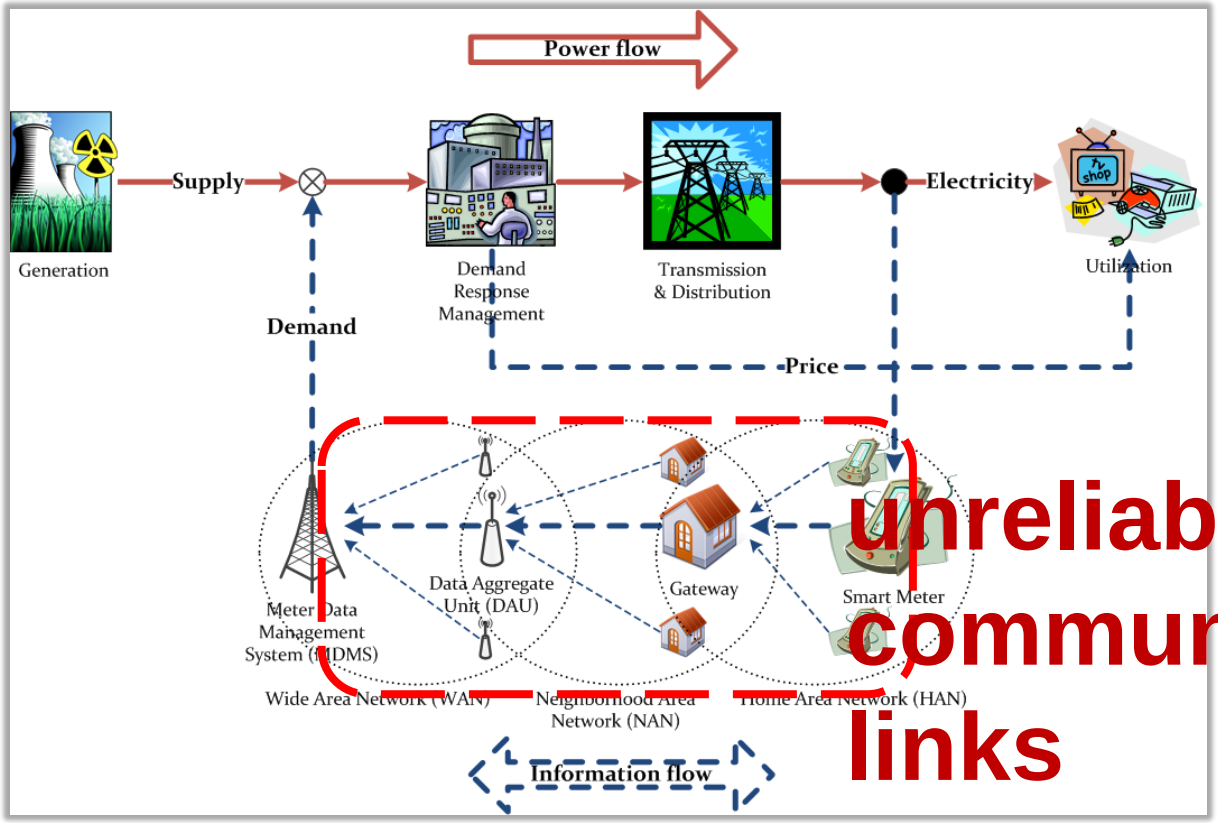
Consequence: both generators and customers can suffer from physical damage (black-out)

Oscillating/diverging prices price leads to system instability



Thanks Prof. David Yau (SUTD) for creating and sharing this slide!

Packet loss may lead to false price



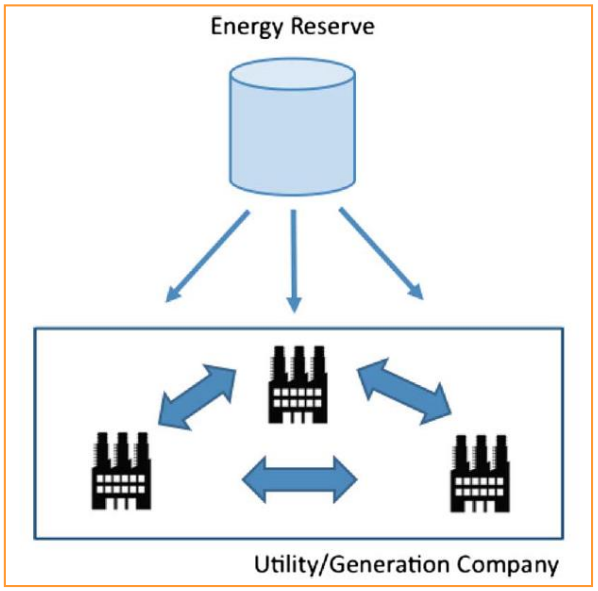
When price information is lost or diverged

- Control unit estimates demand lower than real demand.
- Actual supply will be lower than it should provide, Blackout may happen!

Solutions can be in Energy or Information domains

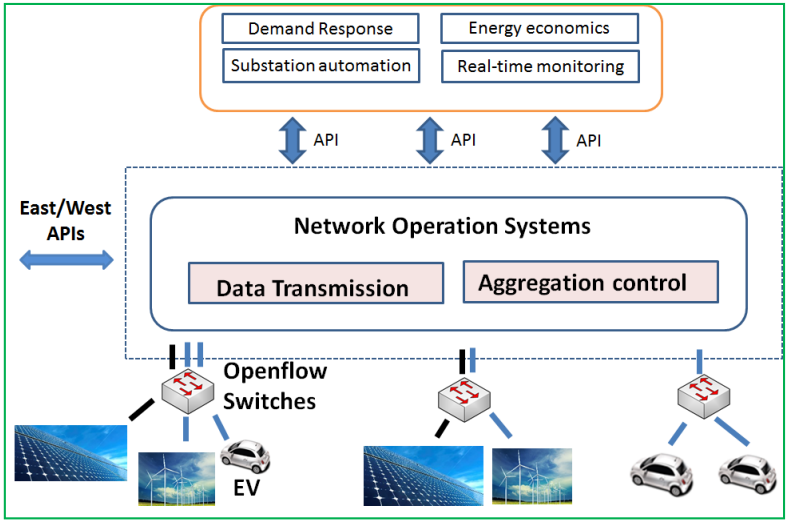
Energy domain

- Distributed or centralized energy storage [w/ Sabita et al. TSG'13]
- Electronic vehicles mobility increases reliability [w/ Zhong et al. TII'16]



Communications & computation domain

- Increase communications quality, e.g., dynamic spectrum [w/ Deng et al. TSG'13]
- SDN adds flexibility [w/Zhong et al. COMMAG'16]



Thank you!