ADVANCED ENERGY
RESEARCH AND TECHNOLOGY CENTER

Smart Grid Optimization

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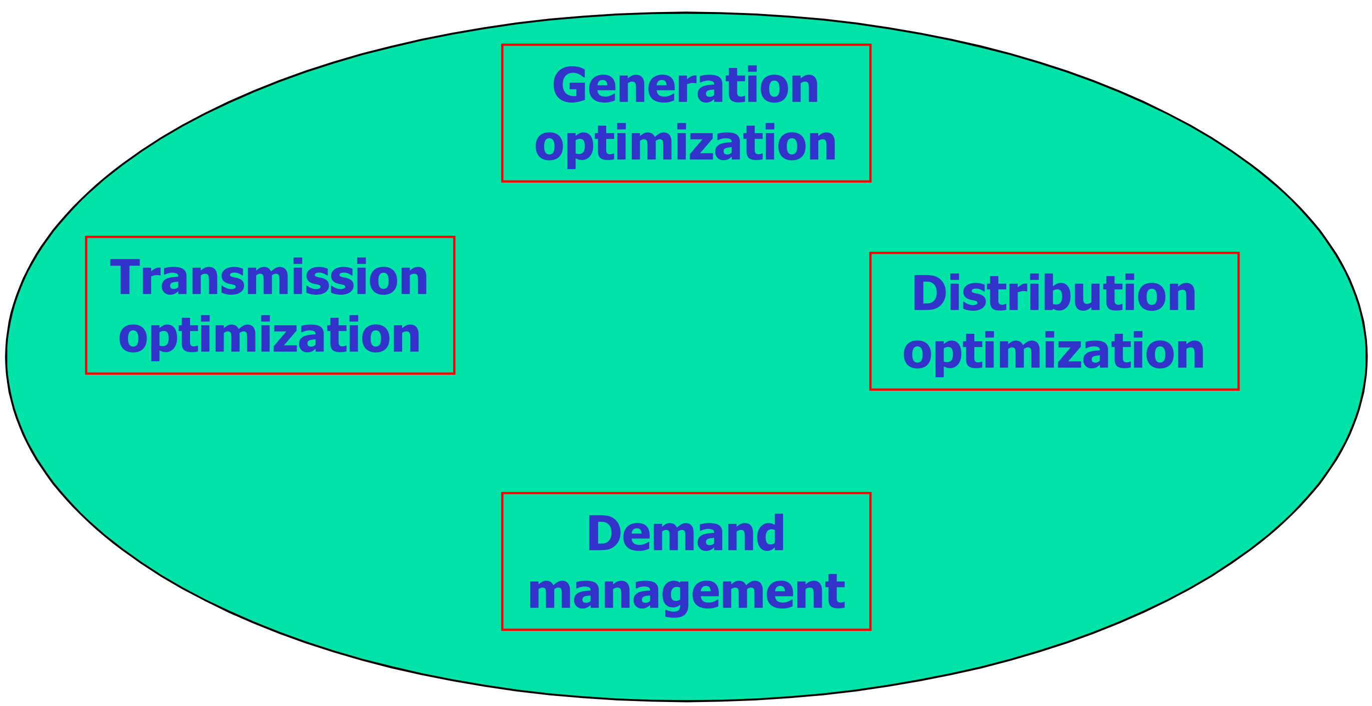
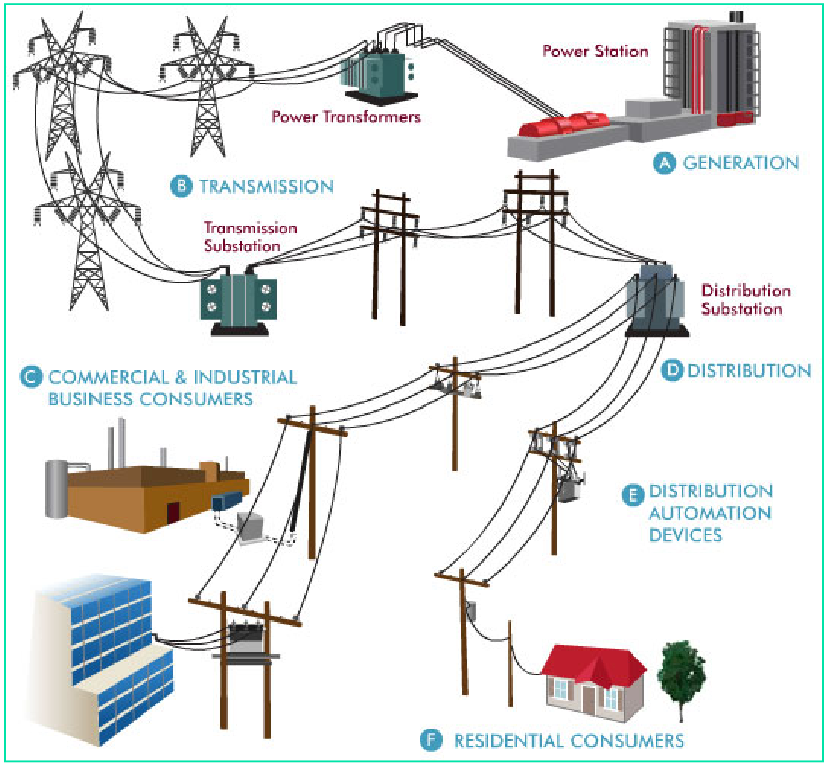
Outline of the tutorial

- Smart Grid: What is it?
- Smart Grid optimization



Traditional power grid

- Most of the current grid was designed and implemented 120 years ago.



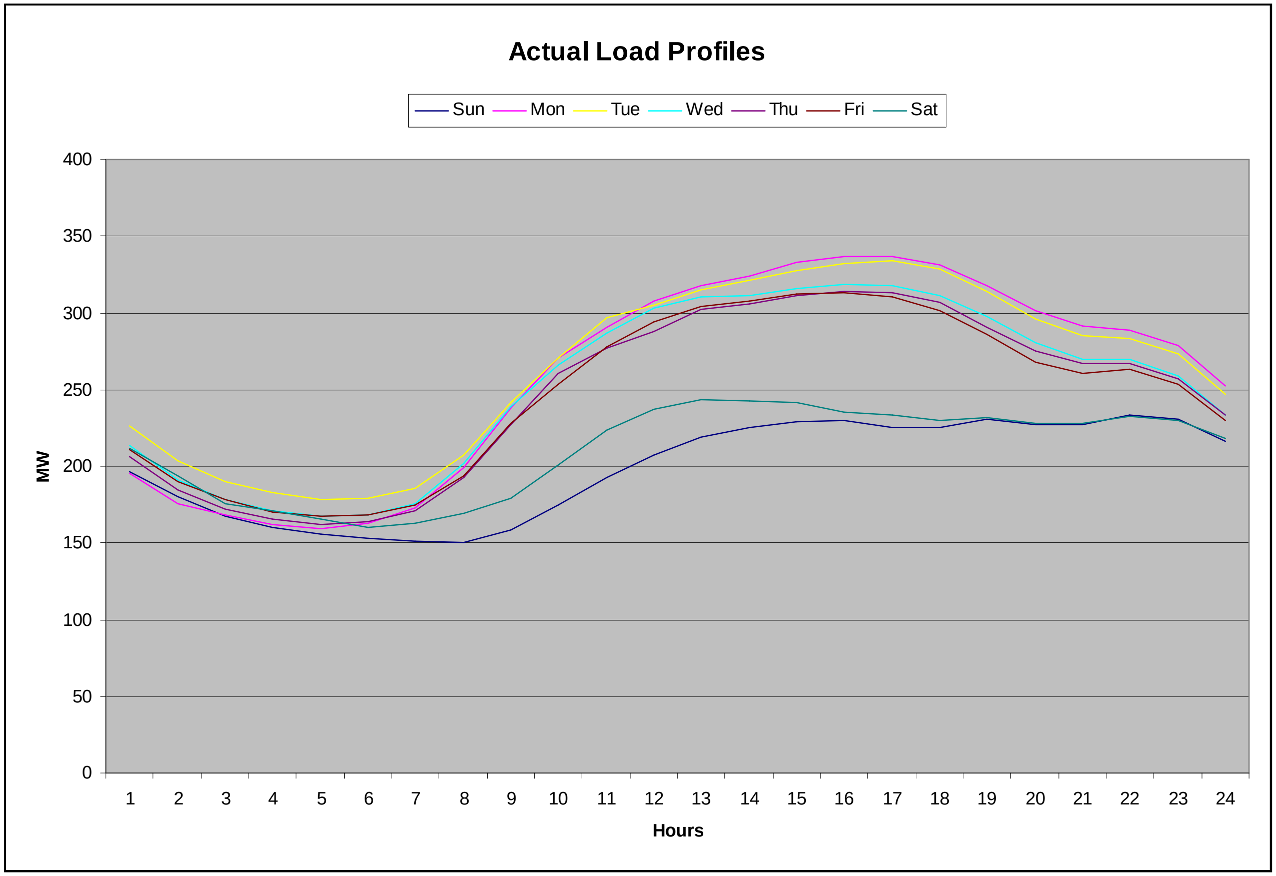
Variation of power demand (load)

- Unlike other commodities electricity cannot be stored, but has to be used when it is generated.
- On the other hand, the power demand (load) changes from time to time. The peak load may be many times as large as the off-peak load.
- This poses challenges to power suppliers because they have to meet the peak demand, resulting low utilization during off-peak times.
- One of the goals of utilities is to reduce peak load so as to reduce the operating costs and defer the new investment to the power grid.

Factors affecting power demand

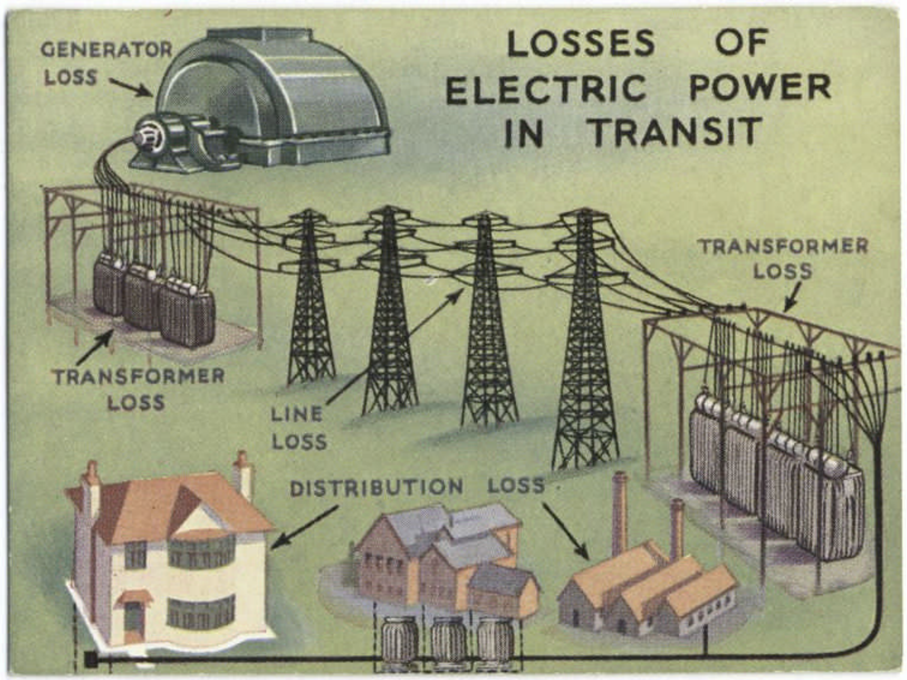
- Time: season of the year, the day of the week, and the hour of the day.
- Weather: temperature, humidity, wind, sky coverage etc.
- Type of consumers: residential, commercial or industrial.

Typical load shape



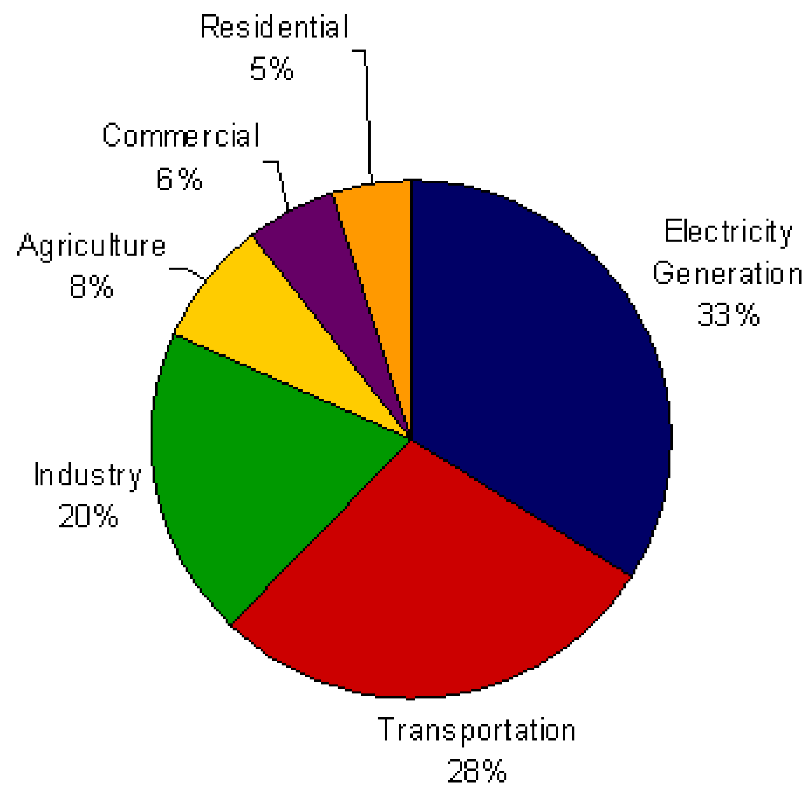
Inefficiency of the traditional grid

- Transmission and distribution losses=6% in the U.S.
- Even worse in other countries
- Source: http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS.



Greenhouse gas (GHG) emissions

- Electricity generation is the largest contributor of GHG emissions.
- In 2006 it contributes 33% to the total GHG emissions.



Percentage of U.S. Greenhouse Gas Emissions, 2006

Power losses

- In 2006, a total of 1,638 billion kWh of energy was lost on the US power grid, with 655 billion kWh lost in the distribution system alone.
- A 10% improvement in distribution system alone would save $5.7 billion (based on 2006 national average electricity price).
- This would also reduce 42 million tons of greenhouse gases emissions.

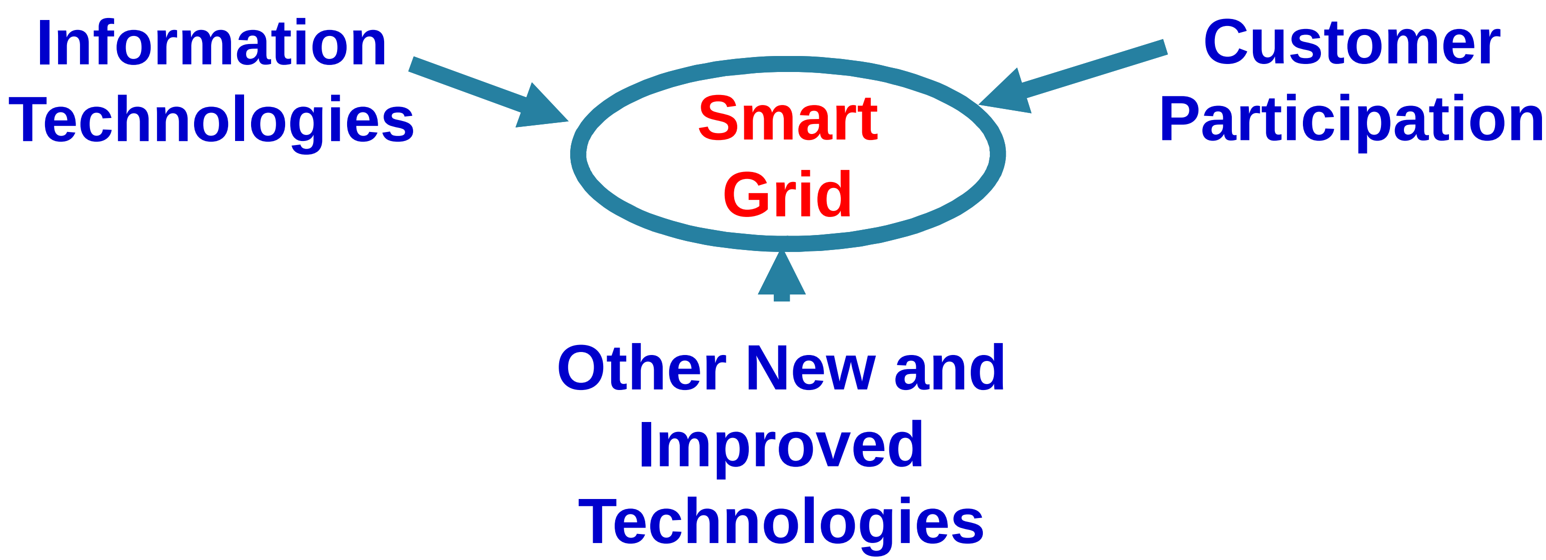
- Source of data:
  - http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3
  - http://www05.abb.com/global/scot/scot271.nsf/veritydisplay/b17d1b6a2ae42b32c125762d004733b7/$file/33-37%203m982_eng72dpi.pdf

Modern challenges posed to the traditional grid

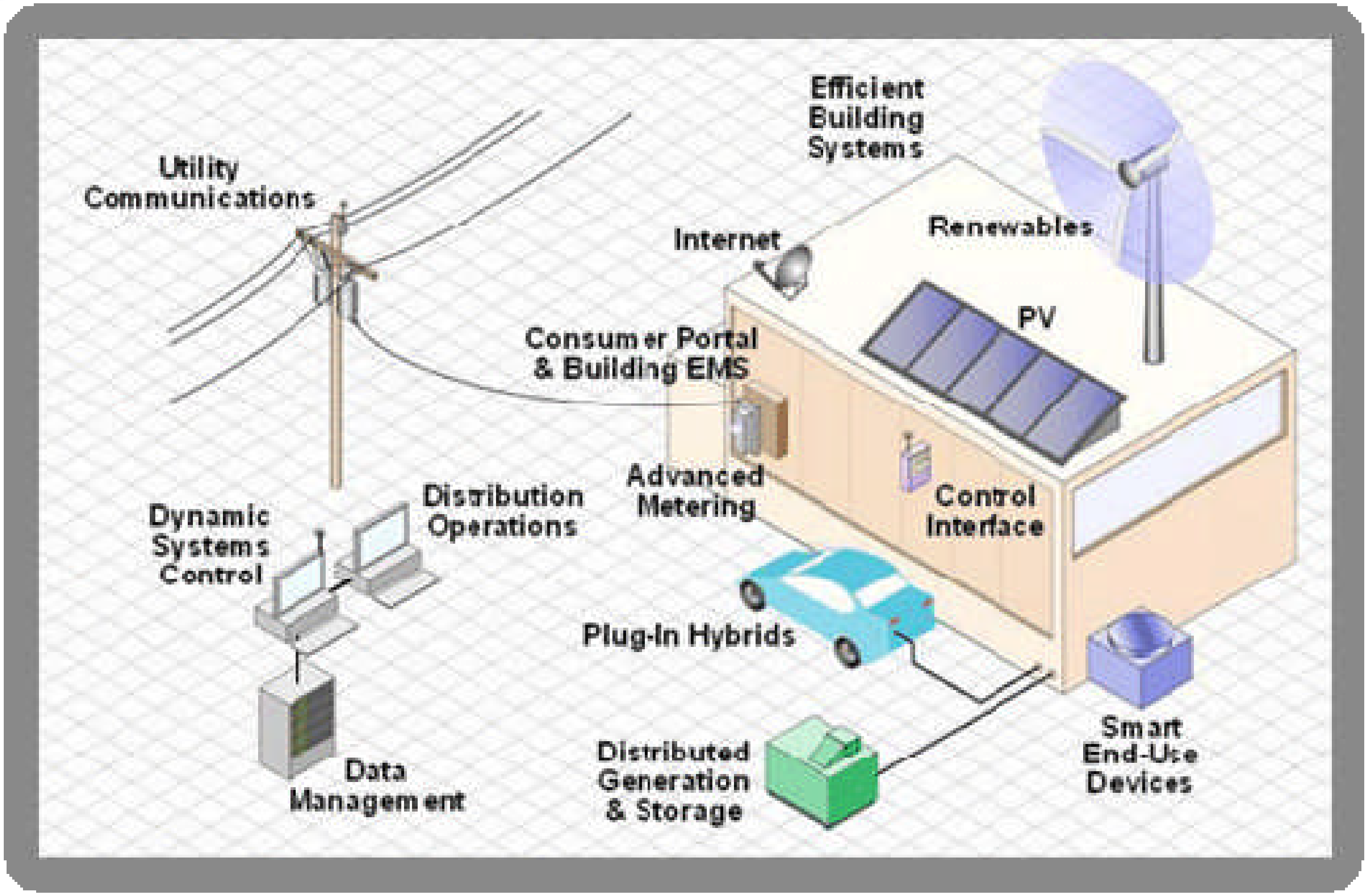
- Over the past 50 years, the traditional grid has not kept pace with modern challenges, such as
  - Security threats, from either energy suppliers or cyber attack
  - More challenges to maintain stable power supply with the entry of alternative power generation sources
  - High demand for uninterruptible electricity supply
  - Poor control and management of distribution network

SmartGrid – An Innovative Concept

- Its importance is compared to the Internet by some analysts.
- It may "spawn new Googles and Microsofts."
- Customer participation and integration of new technologies are key characteristics.



What does a Smart Grid look like?



Key characteristics of Smart Grid

- Enabling informed participation by customers
- Enabling new products, service, and markets
- Accommodating all generation and storage options
- Provide the power quality for the range of needs in the 21st century economy
- Optimizing asset utilization and operating efficiency
- Addressing disturbances through automation, prevention, containment, and restoration
- Operating resiliently against various hazards

Transformation from the traditional grid to a Smart Grid

- **Grid optimization:** Develop the perfect balance among reliability, availability, efficiency, and cost.

- **Demand response and demand-side management:** incorporate automated mechanisms that enable utility customers to reduce electricity use during periods of peak demand and help utilities manage their power loads.

- **Advanced utility control:** monitor essential components, enable rapid diagnosis and precise solutions.

- **Energy storage:** Add technology to store electrical energy to meet demand when the need is greatest.

Transformation from the traditional grid to a Smart Grid

- **Plug-in hybrid electric vehicle (PHEV) smart charging and vehicle-to-grid technologies:** enable electric and plug-in hybrid vehicles to communicate with the power grid and store or feed electricity back to the grid during periods of high demand.

- **Advanced metering:** collect usage data and provide energy providers and customers with this information via two-way communications.

- **Home area networks:** allow communication between digital devices and major appliances so customers can respond to price signals sent from the utility.

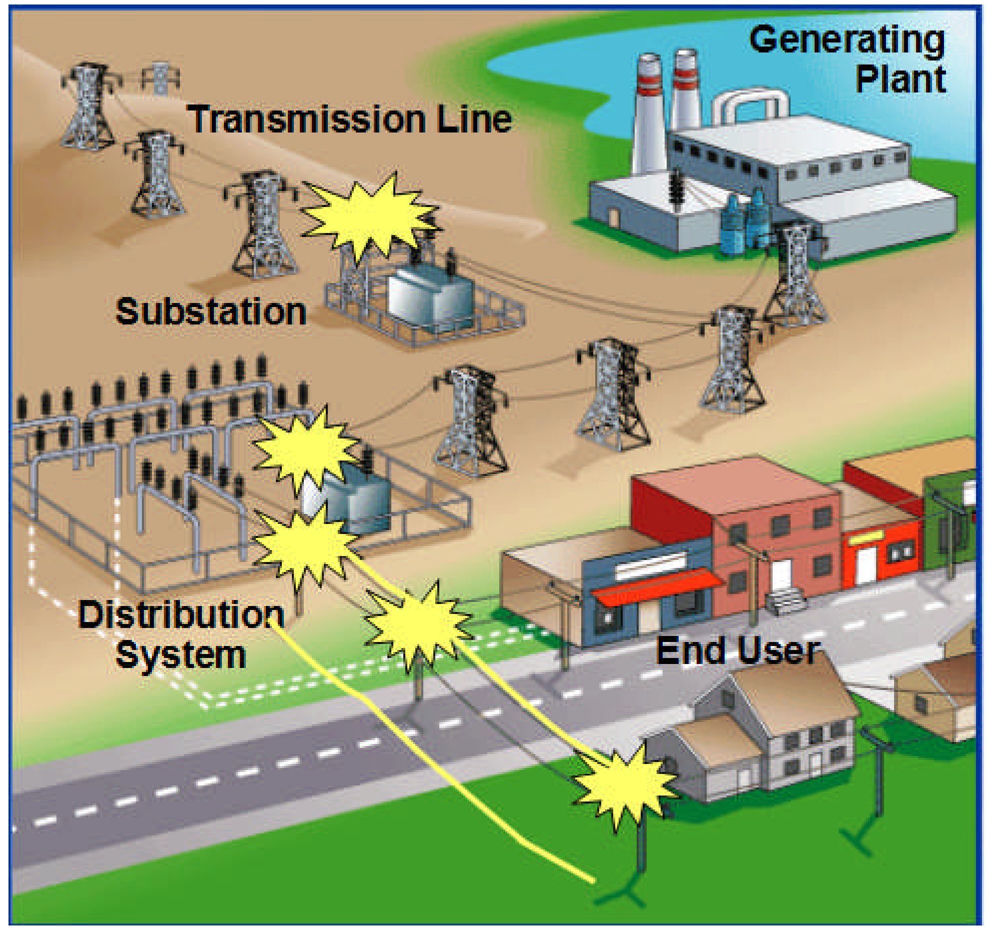
- **Renewable energy and distributed generation sources:** reduce greenhouses gas emissions, provide energy independence, and lower electricity costs.

Key technology – integrated communication

- Fast and reliable communications for the grid
- Allowing the grid for real-time control, information and data exchange to optimize system reliability, asset utilization and security
- Can be wireless, via power-lines or fiber-optics

Key technology – integrated communication

- Broadband over Power-lines
- Monitors and smart relays at substations
- Monitors at transformers, circuit breakers and reclosers
- Bi-directional meters with two-way communication



Key technology – sensing and measurement

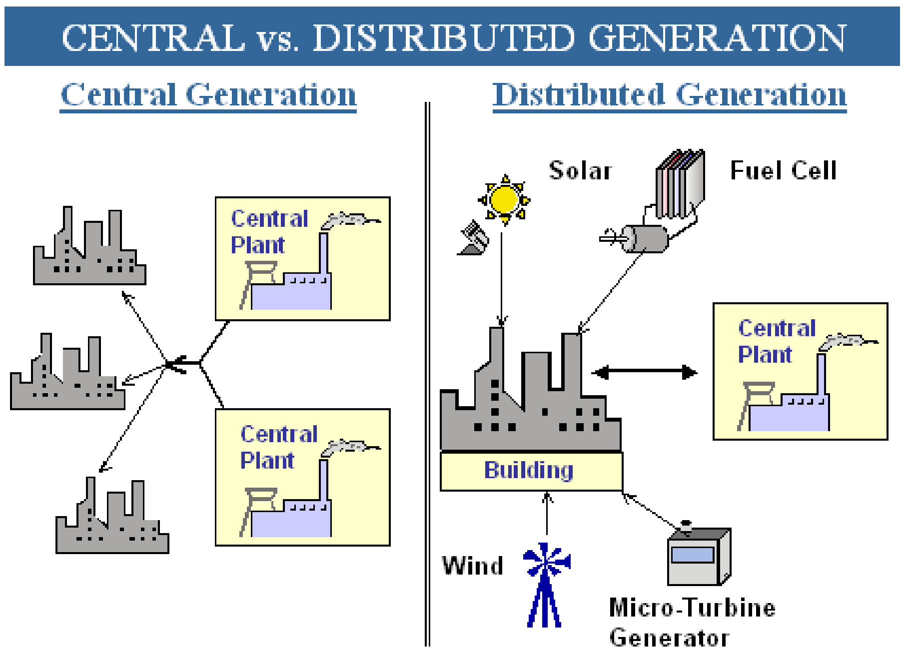
- Smart meter technology, real-time metering of:
  - Congestion and grid stability
  - Equipment health
  - Energy theft
  - Real time thermal rating
  - Electromagnetic signature measurement/analysis
  - Real time pricing
- Phasor measurement units (PMU)
  - Real time monitor of power quality
  - Use GPS as a reference for precise measurement

Key technology – advanced components

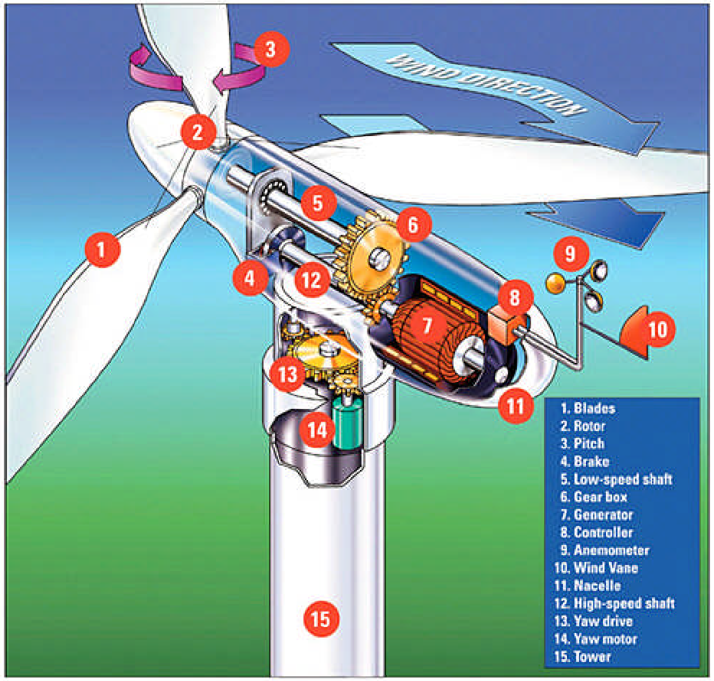
- Distributed energy generation
- Storage devices
- Electric vehicles
- Flexible AC transmission system devices
- Advanced conducting materials
- “Intelligent” appliances

Distributed generation sources

- Small-scale: usually in the range of 3kW to 10MW.
- Examples: wind turbines, solar systems (photovoltaic and combustion), geothermal energy production, and fuel cells.



Renewable generation sources: solar and wind



Grid energy storage in Smart Grid

- In the traditional power grid, electricity must be produced and consumed simultaneously.
- Grid energy storage refers to the methods used to store electricity on a large scale.
- E.g., 50 MW 4-hour battery energy storage can charge during off-peak hours and discharge during peak hours. It takes 4 hours to get fully charged.

Benefits from grid energy storage

- Shift load from peak hours to off peak hours
  - Improve asset utilization of existing infrastructure
  - Reduce investment required for new power plants
  - Reduce investment to increase transmission and distribution limits
  - Transfer lower costs to end-users
- Improve power quality
  - Frequency regulation: With fast spinning reserve (about 10 minutes), grid energy storage can quickly meet the increased demand.
  - Voltage control: grid energy storage supplies reactive power too, which helps maintain satisfactory voltage profiles.

Plug-in hybrid electric vehicle (PHEV) and electric vehicle (EV)

- Plug-in hybrid electric vehicles (PHEVs) are powered by conventional or alternative fuels and by electrical energy stored in a battery.
- Electric vehicles use energy stored in the battery exclusively.

- Potential benefits of using PHEV and EV:
  - Fuel economy
  - Emission reduction
  - Fuel cost saving
  - Energy security – reduce U.S. reliance on imported oil

Key technologies - power system automation

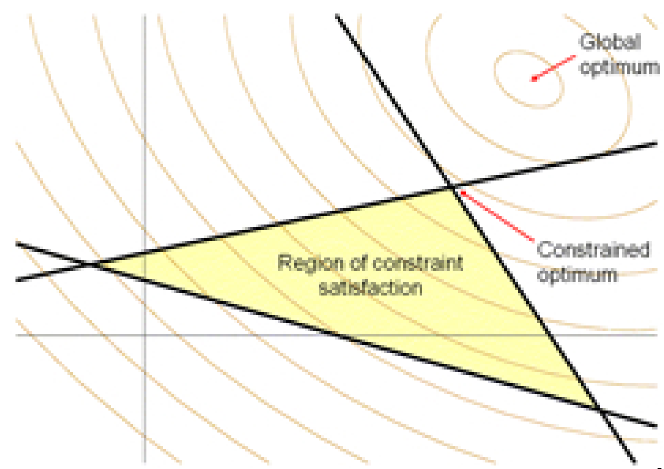
- Rapid diagnosis and precise solutions to specific grid disruptions or outages
- Distributed intelligent agents
- Analytical tools involving software algorithms and high-speed computers
- Operational applications

Key technologies - advanced control methods

- Develop applications that
  - Monitor and collect data from sensors
  - Analyze data to diagnose and provide solutions
  - Determine and take action autonomously or via operators
  - Perform "what-if" predictions of future operating conditions and risks, e.g., fast simulation and modeling

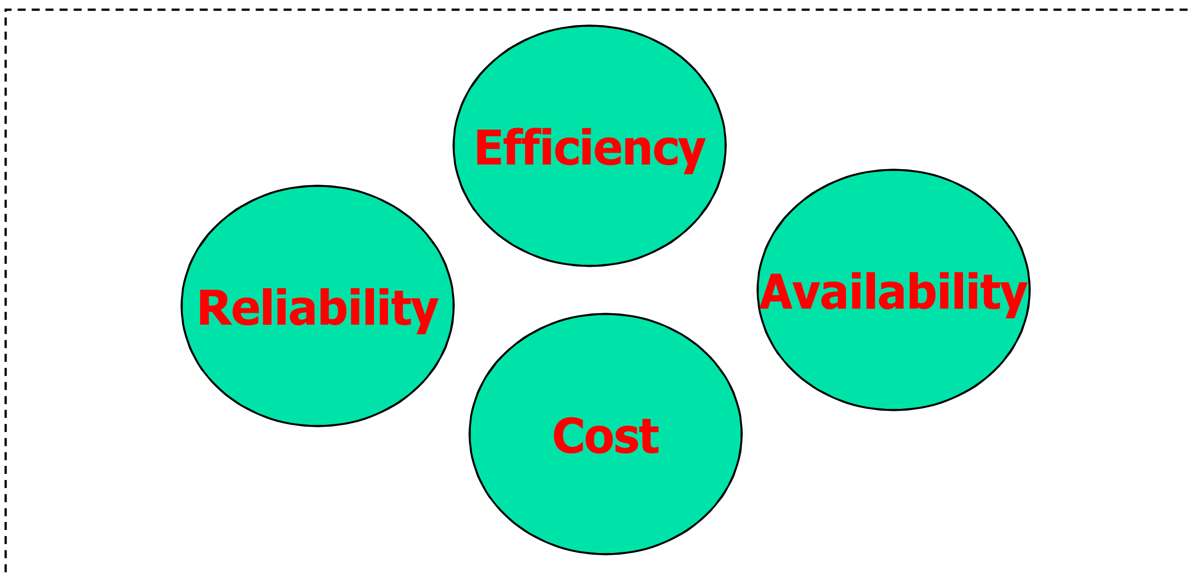
Optimization – mathematical view

- Mathematical optimization refers to the selection of a best element from some set of available alternatives.
- Optimization problems usually consist of three components:
  - Decision variables
  - Objectives
  - Constraints



Smart Grid optimization

- Simply put, Smart Grid optimization is to make the power grid "*as good as possible*".
- We need to find the perfect balance between reliability, availability, efficiency and cost.



Benefits of Grid Optimization

- To improve the utilization of current infrastructure and defer investments in new generation, transmission, and distribution facilities.
- To reduce the overall cost of delivering power to end users.
- To improve the reliability of power grid.
- To reduce resource usage and emissions of greenhouse gases and other pollutants.

Grid optimization in the traditional power grid

- Optimization techniques have been utilized in electric power industry.
- Many well-known optimization problems include unit commitment problem, voltage control problem, and feeder configuration.
- In general optimization has been applied from electricity generation through end-use.

Next-generation grid optimization

- Traditional optimization is based on a model – an estimate of the network's state.
- Smart Grid optimizations is based on real-time information owing to the availability of Advanced Metering Infrastructure (AMI) and two-way communications.

Generation optimization – economic dispatch

- Different generation sources have different economic efficiencies. Some are more efficient and other are not.
- The natural question is: which ones should be run to meet the load demand?
- This is the economic dispatch problem – optimally allocate power generation to generators in order to meet power requirements and other constraints.

Unit-commitment problem (UCP)

Given	Time Horizon – week/month/… Load Forecast Units available for service
Determine	Units that should be placed on line each hour (or day)
Objective	Minimize Cost Fuel+ O&M+ Startup/Shutdown Risk (Probabilistic)
Constraints	Spinning Reserve Emissions Network Ramp rates…

Unit Characteristics – Startup / Shutdown

- Nuclear – shut down only for refueling
- Renewables (Hydro, Solar, Wind) – “zero” resource cost
- Large coal (250+MW): very long start time (days)
- Gas (<200 MW): 8-24 hours start time
- Combustion turbines: as low as 5 Min

Mathematical Formulation

Objective function

- Minimize sum of generation costs, reserve service cost and regulation service costs

Minimize

$$cost = \sum_{m=1}^{M} \sum_{i_m=1}^{I_m} \sum_{t=1}^{T} (F_{m,i_m,t}(p_{m,i_m,t}) + S_{m,i_m,t}(z_{m,i_m,t})) \quad \text{Generation Costs}$$

$$+ \sum_{m=1}^{M} \sum_{i_m=1}^{I_m} \sum_{t=1}^{T} (R_{m,i_m,t}(r_{m,i_m,t})) \quad \text{Reserve Service Costs}$$

$$+ \sum_{m=1}^{M} \sum_{i_m=1}^{I_m} \sum_{t=1}^{T} (CReg_{m,i_m,t}(reg_{m,i_m,t})) \quad \text{Regulation Service Costs}$$

- $p_{m,i_m,t}$ electricity output level of generator i_m in zone m at time period t
- $z_{m,i_m,t}$ binary variable that is 1 if generator i_m in zone m is on during time period t; 0 otherwise
- $F_{m,i_m,t}$ fuel cost function of generator i_m in zone m at time period t
- $S_{m,i_m,t}$ start-up cost function of generator i_m in zone m at time period t
- $R_{m,i_m,t}$ reserve cost function of generator i_m in zone m at time period t
- $CReg_{m,i_m,t}$ regulation cost function of generator i_m in zone m at time period t

Mathematical Formulation

Constraints

- Load balance

$$\sum_{m=1}^{M}(\sum_{i_m=1}^{I_M} p_{i,i_m,t} + w_{m,t}) = d_{m,t} \quad \forall t \qquad w_{m,t}\text{, wind power of zone } m \text{ at time } t$$

- Ancillary service requirements
  - Total and location based reserve requirements that include 10-minute and 30-minute spinning/total reserve requirements:

$$\sum_{m\in\Lambda_j}\sum_{i_m=1}^{I_m} r_{m,i_m,t} \geq Res_{j,10spin} \quad \forall j,t \quad \Lambda_j: \text{the } jth \text{ set of zones}$$

  - Regulation requirement:

$$\sum_{m=1}^{M}\sum_{i_m=1}^{I_m} reg_{m,i_m,t} \geq Reg_t \quad \forall t$$

- Transmission constraints

$$tran_l \leq Tran_{l,max} \forall l$$

- Single generator capacity constraints

$$p_{m,i_m,t} + r_{m,i_m,t} + reg_{m,i_m,t} \leq p_{m,i_m,max}$$

Probabilistic Unit Commitment Model with Wind Power

Model description

- Assume a certain power outage level □; a new reserve constraint is obtained:

$$\mathrm{P}\{\sum_{m=1}^{M}\sum_{i_m=1}^{I_m} p_{m,i_m,t} + \sum_{m=1}^{M}\sum_{i_m=1}^{I_m} r_{m,i_m,t} \geq \sum_{m=1}^{M} d_{m,t} - \sum_{m=1}^{M} w_m, \forall t\} \geq 1-\alpha$$

Use Bonferroni's inequality, we have:

$$\mathrm{P}\{\sum_{m=1}^{M}\sum_{i_m=1}^{I_m} p_{m,i_m,t} + \sum_{m=1}^{M}\sum_{i_m=1}^{I_m} r_{m,i_m,t} \geq \sum_{m=1}^{M} d_m - \sum_{m=1}^{M} w_{m,t}\} > 1-\frac{\alpha}{T}$$

Assume $w_{m,t} \sim N(\mu_{m,t}^{w}, {\sigma_{m,t}^{w}}^{2})$, then, we have:

$$\sum_{m=1}^{M}\sum_{i_m=1}^{I_m} p_{m,i_m,t} + \sum_{m=1}^{M}\sum_{i_m=1}^{I_m} r_{m,i_m,t} \geq \sum_{m=1}^{M} d_m - \sum_{m=1}^{M} \mu_{m,t}^{w} + z_{1-\frac{\alpha}{T}} \sum_{m=1}^{M} \sigma_{m,t}^{w}$$

Rolling Horizon Scheme

- At each time t, updated wind power forecasts is obtained
- Update the reserve constraints, and solve the unit commitment problem with respect to the next T time periods

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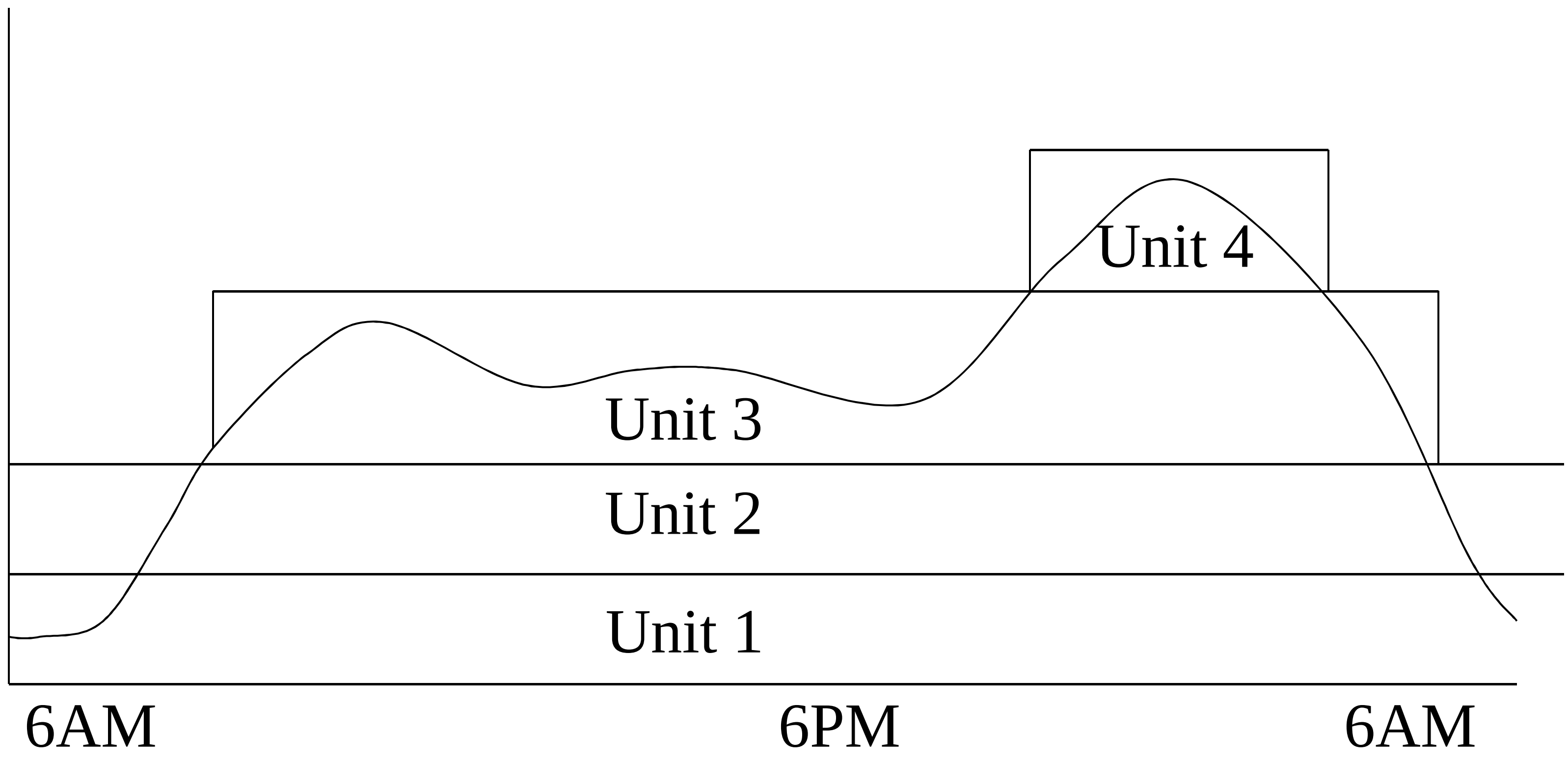
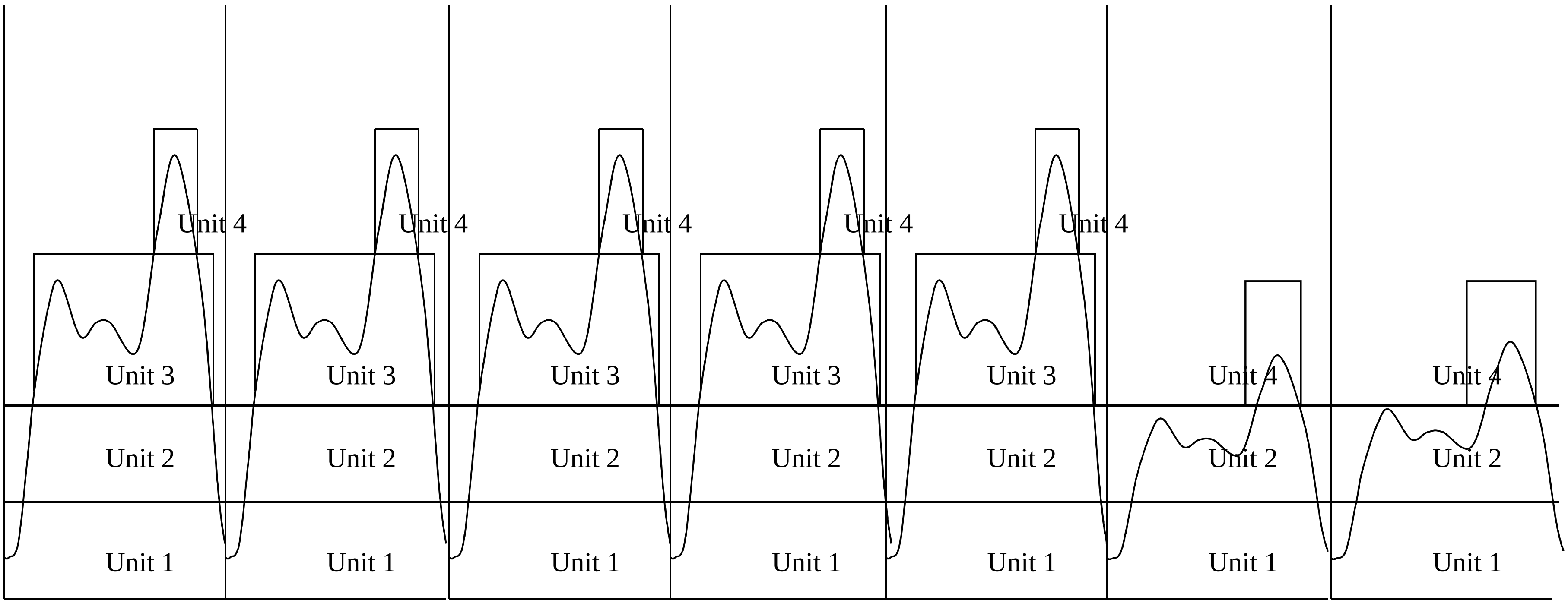
Solution methods to UCP

- Heuristic methods
- Mixed integer programming
- Benders decomposition
- Dynamic programming
- Lagrangian relaxation
- Utilization of parallel computing

UCP solution – daily schedule

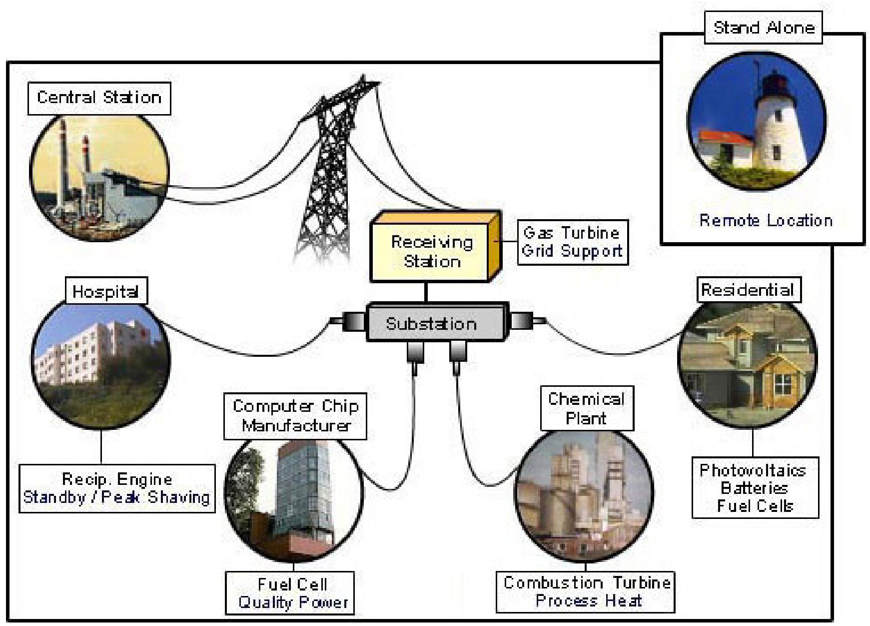


UCP solution – weekly schedule



Generation optimization with the presence of distributed generations (DG)

- One characteristic of Smart Grid is to accommodate distributed generations (DG) including fuel cells, renewables, microturbines etc.
- DGs are more uncertain, which makes dispatching decisions even more challenging. E.g., it is hard to predict near-term wind availability and velocity.



Some reasons for DG

- DG units are closer to customers. Therefore Transmission and Distribution (T&D) costs are reduced.
- It is easier to find sites for small generators.
- Natural gas as fuel in DG stations is easily accessible and prices are more stable.
- Usually DG plants require shorter installation times and the investment risk is not too high.

Optimal placement of DG

- DG devices can be strategically placed in power systems for grid reinforcement.
- Benefits include:
  - reducing power losses and on-peak operating costs
  - improving voltage profiles and load factors
  - differing or eliminating for system upgrades
  - improving system integrity, reliability, and efficiency

Optimal placement of DG

- Objectives include
  - minimization of active power losses
  - Maximizing DG capacity
  - Minimization of loading in selected lines
- Constraints include voltage, thermal, short circuit, and generator active and reactive power capabilities.

Transmission optimization

- Transmission networks are usually huge in size, running through several states or even across the international boundaries.
- They are interconnected, which means that the failure of one region may cause the collapse of the whole network.
- For this reason, security and reliability issues are of vital importance.

Transmission optimization – faster power flow solver

- Minimization of operating margins or maximum utilization of existing transmission assets with increased system security and reliability requires new control equipment to perform power flow computation on the order of milliseconds.
- Fast solutions of large-scale algebraic equations are critically important for timely power control calculations.
- Scale of transmission network: 10,000 or more buses, or 20,000 by 20,000 Jacobian matrix.
- Desirable computing time: milliseconds.

Faster power flow solver - methods

- Jacobian-free Newton–Krylov (JFNK) method to solve nonlinear algebraic systems of equations.
- Parallel computing scheme on modern architecture supercomputers using multilevel parallelization techniques.

Faster power flow solver in a Smart Grid

- Smart Grid makes fast power flow solver even more critical.
- Installations of new generation of sensors, such as Phase Measurement Units (PMUs), and integrated telecommunication networks provide faster updates of information on network components.
- Coupled with faster power flow solver, all of this allows faster computation and faster decision making including state estimation, fault detection & location, and quick restoration.

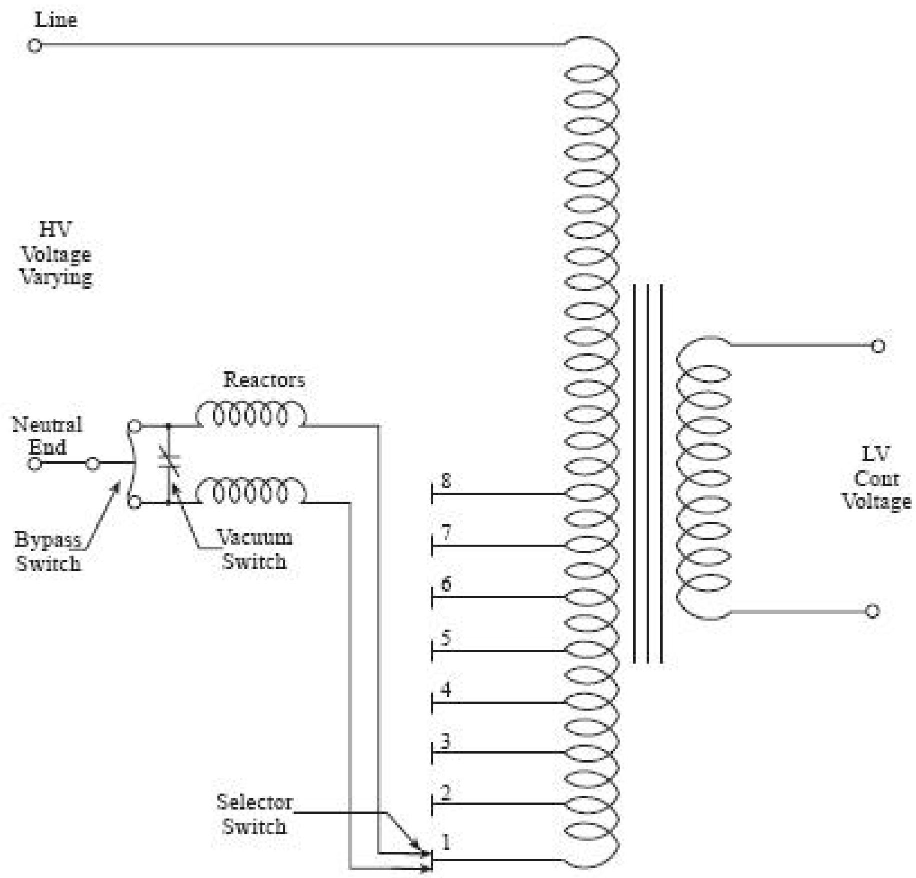
Distribution optimization

- Voltage control
- Feeder configuration
- Phase balancing

Voltage control

- The purpose of voltage control in distribution networks is to change the tap position of transformer regulators in order to achieve the goal of reducing power losses while maintaining satisfactory voltage profiles.
- The change of voltage is through a number of on-load tap changers (OLTCs), each capable of regulating the voltage of the secondary side of a transformer at one point in the network.

On-load tap changer



On-Load Tap Changer

Voltage control model

- Minimize power losses and switching (tap change) costs

  Subject to:
  - power flow equations;
  - voltage constraints, both phase to neutral and phase to phase;
  - current constraints, including cables, overhead lines, transformers, neutral and grounding resistance;
  - tap change constraints
  - shunt capacitor change constraints

Conservative Voltage Reduction

- Conservative Voltage Reduction (CVR) is the concept of lowering the utilization voltage to end-use consumers such that their demands, and energy consumption, decreases.
- The most prominent benefit of CVR is the peak load reduction, which accordingly reduces the cost of power delivery because it costs more to run peaking generation units.
- CVR has another benefit of reducing power loss.
- CVR usually makes use of both capacitors and voltage regulators.

Feeder reconfiguration under distributed generation conditions

- Feeder reconfiguration is to alter the topological structures of distribution feeders by changing the open/closed states of the sectionalizing or tie switches.
- The goal is to minimize the total system power loss while keeping the generation cost of distributed generators at minimum.

Benefits of feeder configuration

- Improve network load balancing
- Reduce power losses
- Prevent service disruption in case of power outage

Model formulation

- minimize the total system losses over a planning horizon *L*:

$$\min \ G := \sum_{h=0}^{L} \left(\sum_{i=1}^{N} |I_{i,h}|^2 R_i + C \cdot S_h \right)$$

$$\text{subject to : voltage, transfer capacity and network constraints}$$

  - N: number of load sections
  - $I_{i,h}$: the electric current on load section i at time h
  - R_i: the resistance of load section i
  - C: cost incurred per switching operation
  - S_h: number of switching actions at time h

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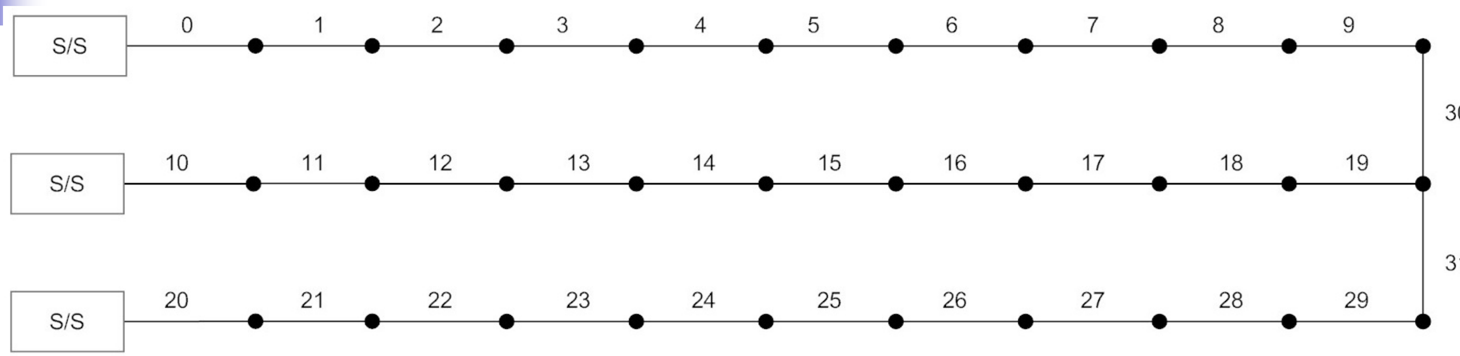
Feeder reconfiguration – solution approaches

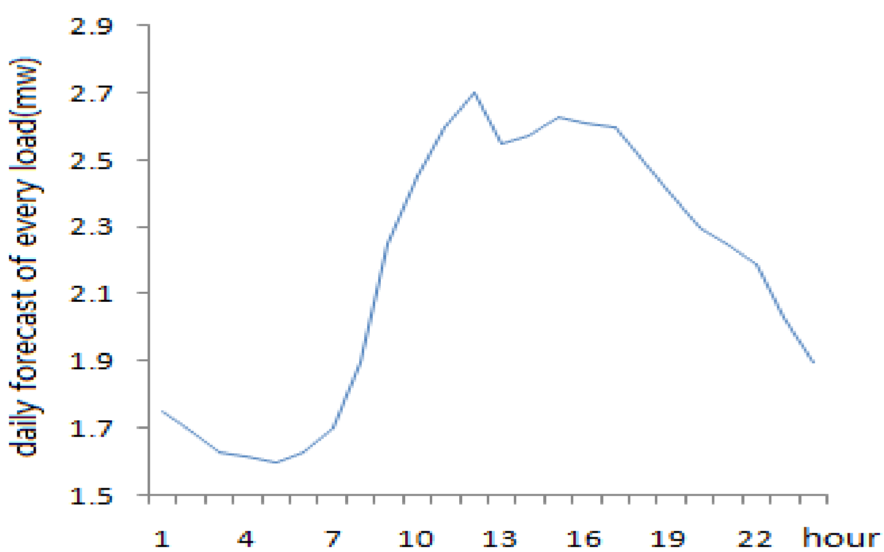
- Most of the existing feeder reconfiguration approaches have primarily centered around the issue of how to efficiently solve the underlying discrete optimization problem.
- These approaches include genetic algorithms, Tabu search, heuristic methods, and dynamic programming.
  - Genetic algorithms (Sivanagaraju et al. 2006; Koichi et al. 1992)
  - Tabu search (Rugthaicharoencheep and Sirisumrannukul 2009)
  - Heuristic methods (Milani et al. 2008; Zhou et al. 1997)

A Numerical Example

- 3 feeders, 30 load points, and 32 switches with 30 and 31 being tie switches



- mean of daily load forecast on a load section *L*(*h*), *h=1:24*



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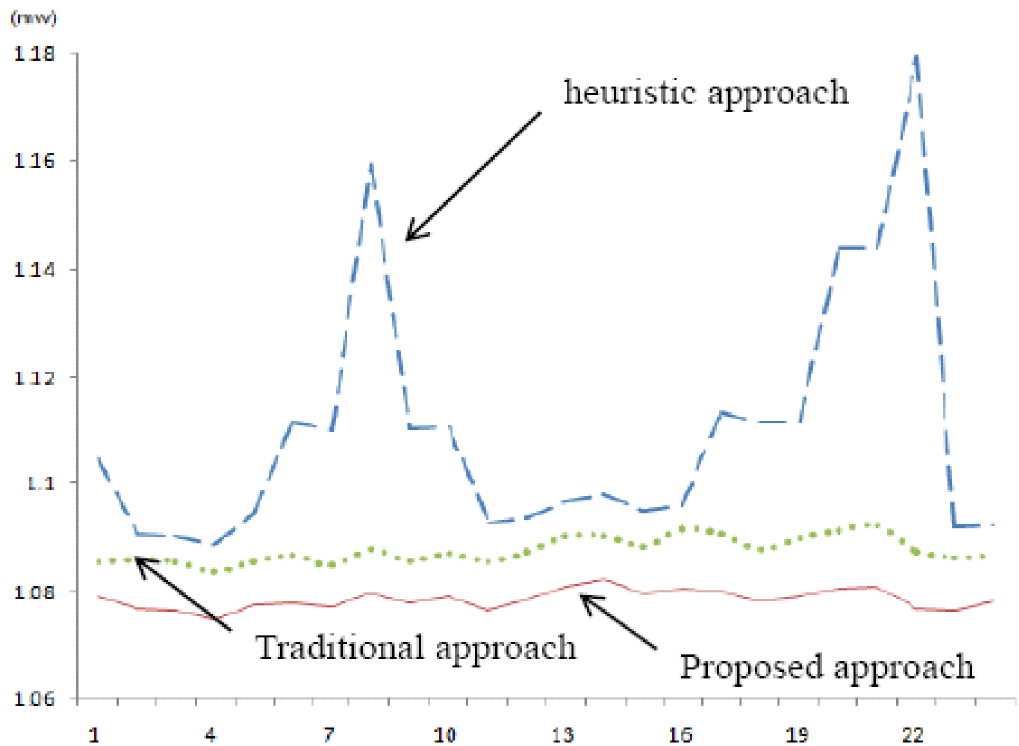
A Numerical Example

- Test case I: hourly load forecast on all sections follow a normal distribution $N(L(h), 490000\text{kw}^2)$
  - ➢ total power losses+ switching costs over the 24 hour period
  - ➢ heuristic approach: the two tie switches remain open and the rest of the switches remain closed at all time



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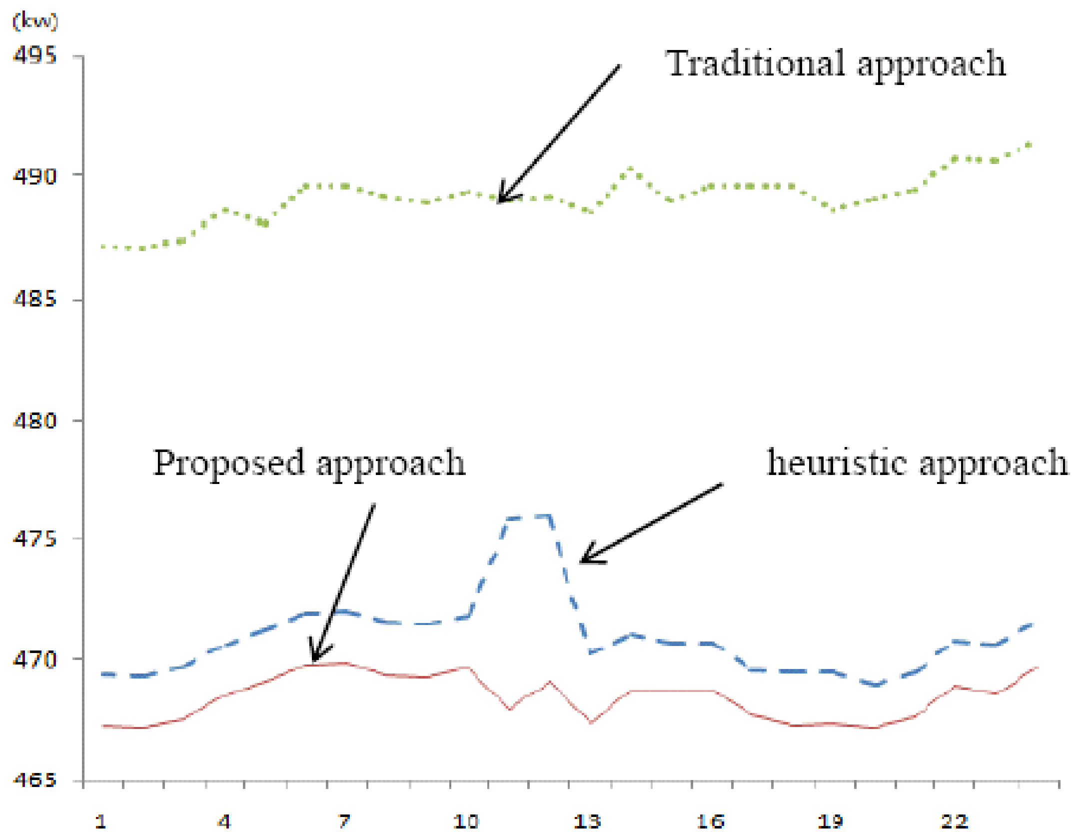
A Numerical Example

- Test case II: hourly load forecast on all sections follow a normal distribution $N(L(h), 360000\text{kw}^2)$
  - ➢ total power losses+ switching costs over the 24 hour period



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Phase balancing

- The goal of phase balancing is to maximize the feeder capacity utilization, to improve power quality, and to reduce energy losses.
- It is a “combinatorial optimization” problem. The solution is the assignment of customer load to which of the three phases.
- Standard algorithms for such problems are tabu search, simulated annealing, genetic algorithms and exhaustive search.

End-use optimization

- Load forecasting
  - Substation transformer level
  - Feeder level
  - Section level
- Demand management
  - Load shifting

Load Modeling and Forecasting using AMI data

- With AMI, load modeling and forecasting can be conducted in an even more flexible and useful way, and at even lower levels – section or even customer level.
- This load modeling and forecasting provides valuable inputs to other distribution applications – such as optimal power flow, reliability simulation, feeder configuration, phase balancing, and voltage control.

Importance of load forecasting

Load forecasts are extremely important for electric utilities especially after deregulation. They can help them save significant resources, such as

- Purchasing, generation, sales
- Contracts
- Load switching
- Area planning
- Infrastructure development/capital expenditure decision making

Types of Load Forecasting

Load Forecasts

- Short term forecasts (one hour to a week)
- Medium forecasts (a month up to a year)
- Long term forecasts (over one year)

Short-term Load Forecasting at Different Levels

- System level: provide forecasts for the entire region as the whole
- Load pocket and transformer level: provide forecasts for a transformer or a set of transformers (defined as load pockets)
- Feeder level: provide forecasts for a particular feeder

Substation and transformer level load forecasting

- Transformer level load forecasting can be used as inputs for transformer rating calculation.
- It provides necessary warning for transformer overloading or overheating.
- Operators can take appropriate actions to transfer the loads so as to protect the valuable asset.

Feeder level load forecasting

- The goal is to provide the system operators with advanced warnings on potential feeder overloading.
- The forecasting can be used as inputs to feeder reconfiguration application that we discussed earlier.
- System-wide feeder level load forecasting can be extremely useful for operators to come up an optimal switching and load transfer decisions.

Section level load forecasting

- Consider a feeder that is separated with a few switchers. Each separated segment is called a section.
- With AMI we can obtain load information for each section and each end customer.
- We also have information for each of the three phases.
- These forecasting would be valuable inputs for optimal switching decisions and phase balancing.

Load forecasting models

- Given a model:
- $yt = Ft(dt, ht, wt, pt) + et$
-
- where yt is the actual load at time t;
- Ft is the model specification;
- dt is the day of the week, 1, 2, …, 7;
- ht is the hour of the day, 0, 1, …, 23;
- wt are weather parameters including the temperature and humidity;
- pt are other factors including electricity prices, sunrise and sunset times;
- et is a random error.

Model estimation – Least Square method

- Least square method is used to minimize the total squared residues:

$$\min \Sigma_{\mathrm{t}}[y_t - F_t(d_t, h_t, w_t, p_t)]^2$$

- This is an unconstrained nonlinear optimization problem.
- Nonlinear programming methods such as trust region, Newton-Raphson, quasi-Newton, double dogleg, conjugate gradient, and Levenberg-Marquardt (LM) can be used.

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Load forecasting – performance measures

- Performance Measures

  - Mean Absolute Percentage Error (MAPE)

$$MAPE = \frac{1}{N}\sum_{i=1}^{n}\frac{|y_t - F_t|}{y_t},$$

  - Mean Absolute Deviation (MAD)

$$MAD = \frac{1}{N}\sum_{i=1}^{n}|y_t - F_t|.$$

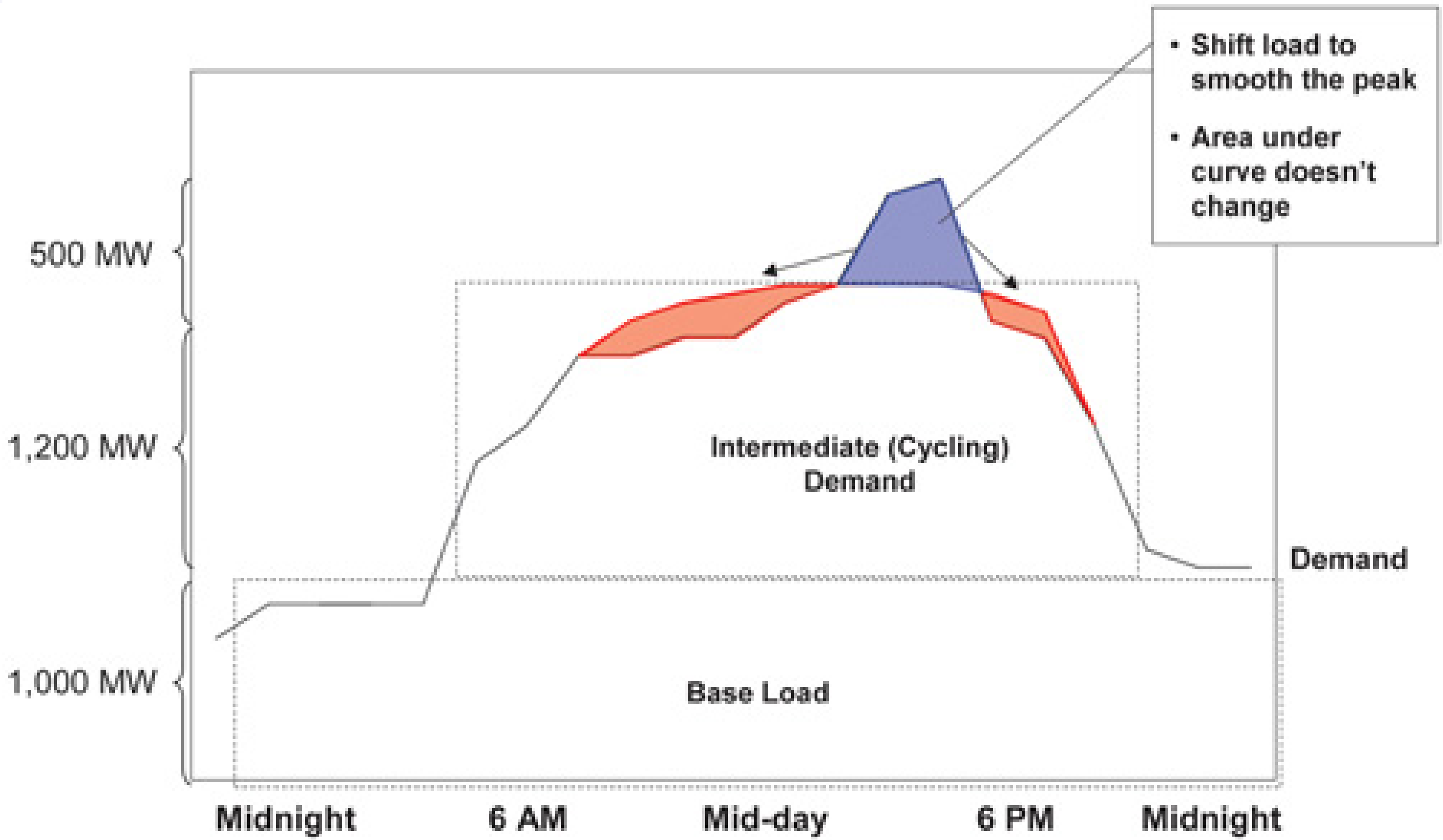
Demand management

- Demand management works to reduce electricity consumption in homes, offices, and factories by continually monitoring electricity consumption and actively managing how appliances consume energy.
- It consists of demand-response programs, smart meters and variable electricity pricing, smart buildings with smart appliances, and energy dashboards.
- Combined, these innovations allow utility companies and consumers to manage and respond to the variances in electricity demand more effectively.

Load shifting (shedding) with smart meters

- Currently most retail consumers are charged a flat price for electricity regardless of the time of day or actual demand. So they have little incentive to lower their energy use to reduce their energy bill while helping utility companies meet demand.
- With smart meters give customers the ability to choose variable-rate pricing based on the time of day. By seeing the real cost of energy, consumers can respond accordingly by shifting their energy consumption from high-price to low-price periods.
- This process can have the joint benefit of reducing costs for typical consumers while lowering demand peaks for utility companies.

Sample load reduction



Conclusions

- With grid optimization we can find the perfect balance between reliability, availability, efficiency and cost.
- Grid optimization ranges from generation to transmission and from distribution to end-user.
- All of these rely on key Smart Grid technologies, namely integrated telecommunication and sensing and measurement.