EE4511
Renewable Generation and Smart Grid

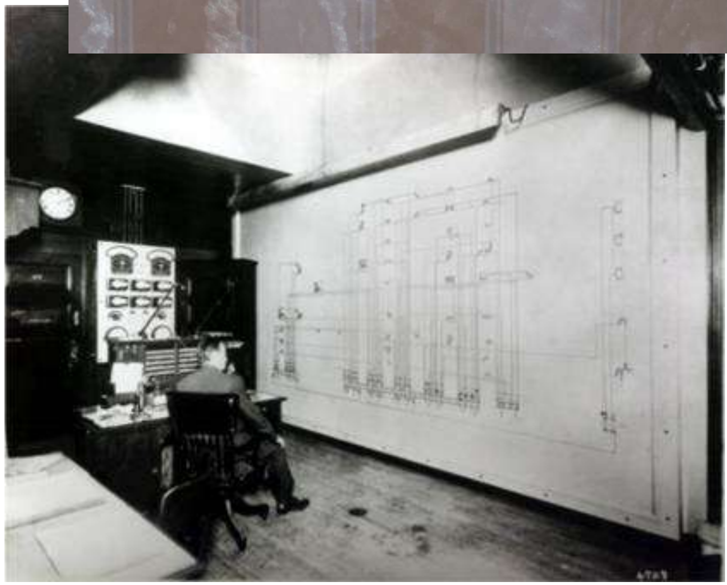
Smart Grid and Energy Economics

NUS National University of Singapore

Learning outcomes:

1. Understand what is a Smart grid
2. Understand the roles of smart grid towards enhancing the sustainability of electric energy systems
3. Understand Utility Rate structure
4. Demand Side Management and Energy Efficiency
5. Summarize the key features and potential advantages of future smart grid
6. Understand what is a Micro grid
7. **Discuss recent developments and case studies**

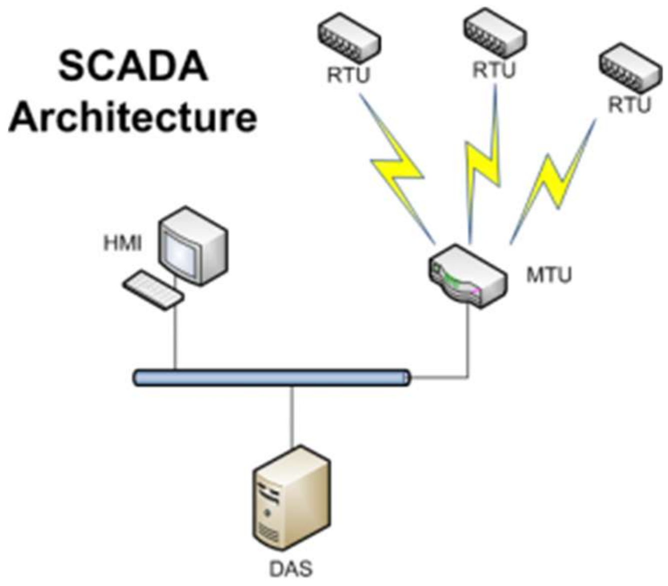
Present Day Grid Perception



SCADA

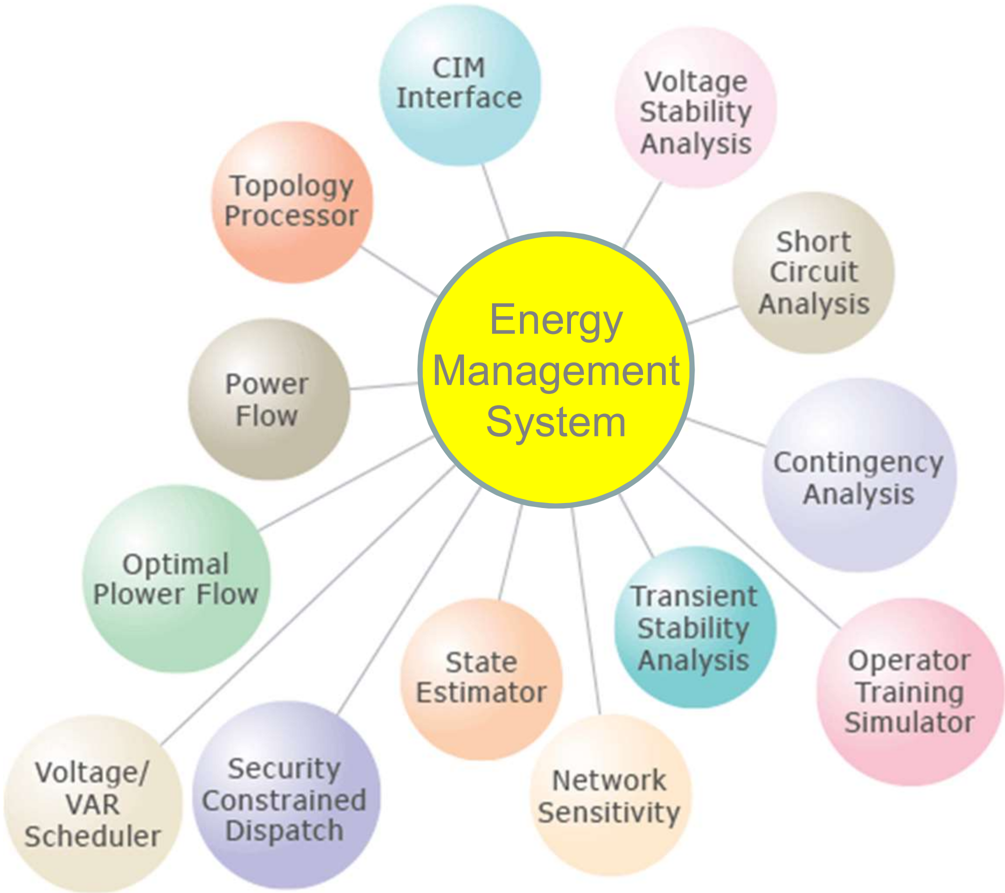
Supervisory control and data acquisition

- Interfaces in the field (substations) to equipment and devices.
- Provides information on real and reactive power, current, voltage, and switch and circuit breaker positions.



EMS – Energy Management System

EMS is a **system of computer-aided tools** used by system operators to **monitor**, **control**, and **optimize** the performance of the generation and transmission systems.



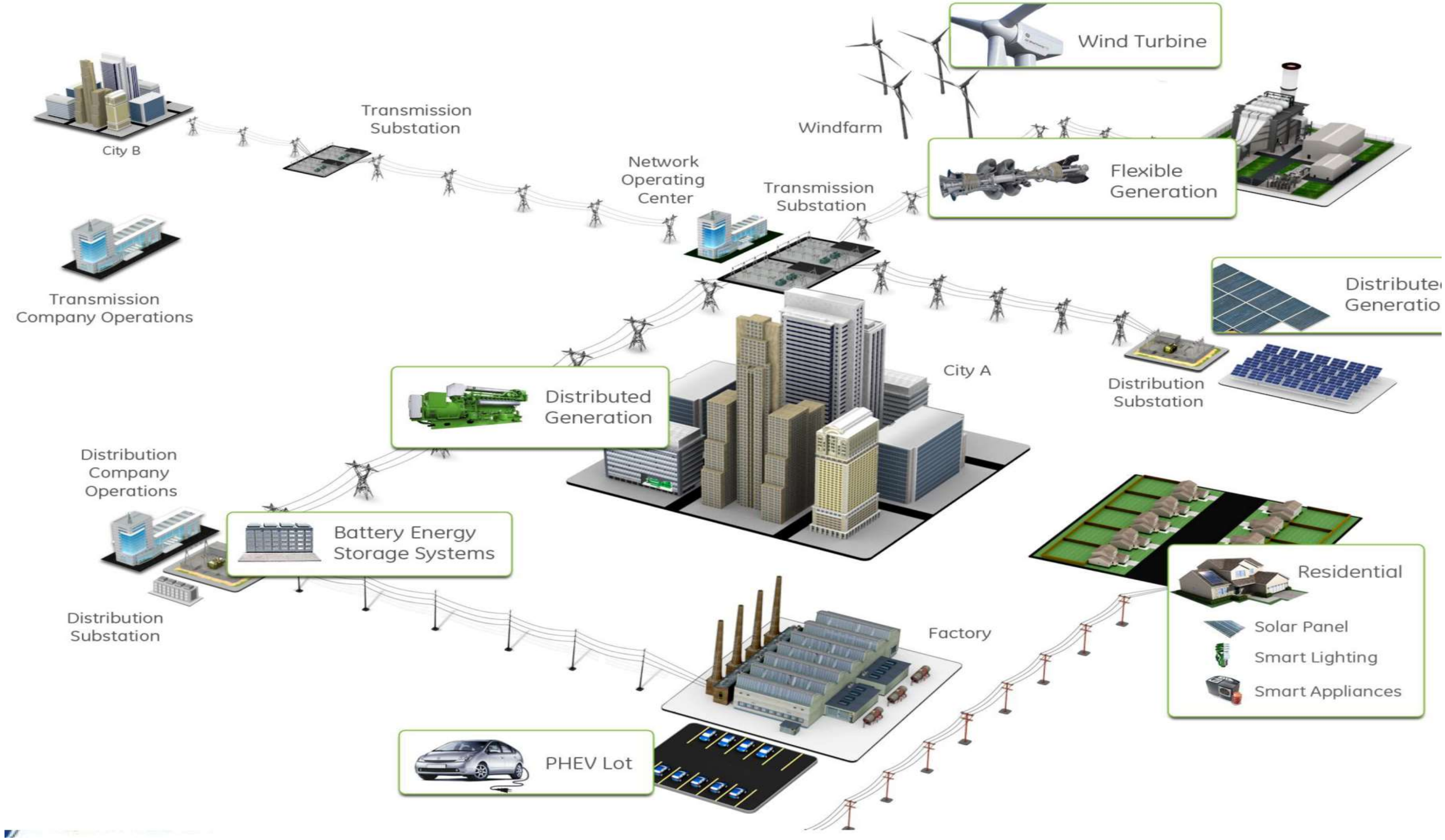
Smart Grid

- **The Grid has always been smart**
- **It's getting smarter !!!**

- Significant change in the way power supply system is designed and operated
  - Improved operational efficiency
  - Reduced environmental impact
  - More customer choice

Through application of new technology

Growing complexity of modern grids

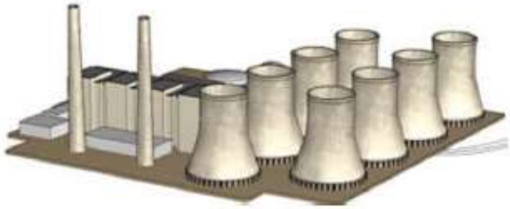


Smart Grid ... Key Drivers

Economy

Policy & Regulations

Aging Infrastructure



Energy Security

Technology

Environment

Every region has unique challenges, opportunities, and priorities

Driving Forces of Change

Environment - Rising Greenhouse Gas Emissions (CO2) have the potential to seriously impact the environment and local economies.

Innovative Technology holds significant promise as a “game changer.” Innovation is pervasive across the electricity value chain (from smart appliances to advanced energy storage technologies).

Economic factors

Improvements in economics are realized when energy and delivery bills paid by consumers are lower than they otherwise would have been. The creation of opportunities for new products and services, thestimulation of economic development and the U.S. GDP, and the creation of new jobs are all elements of improved grid economics.

Driving Forces of Change

Environment

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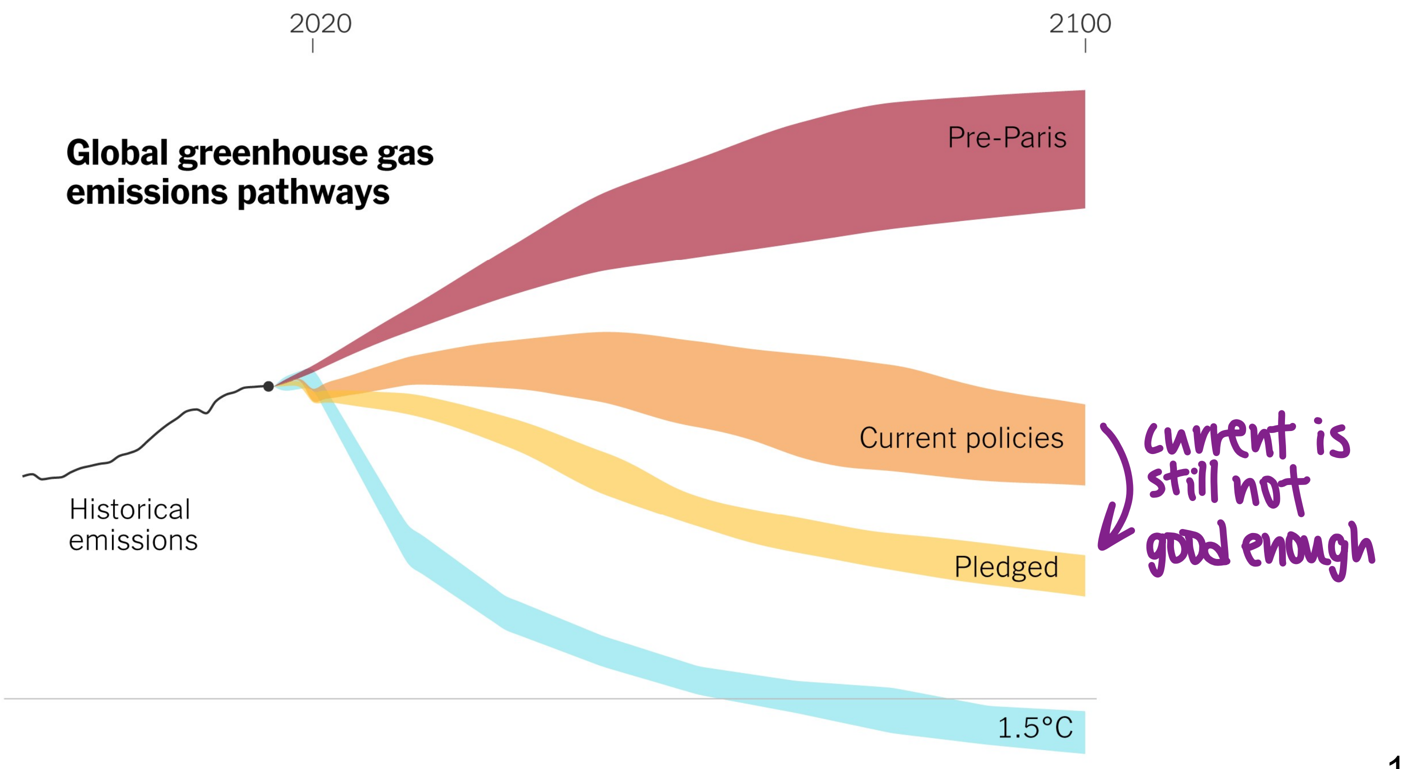
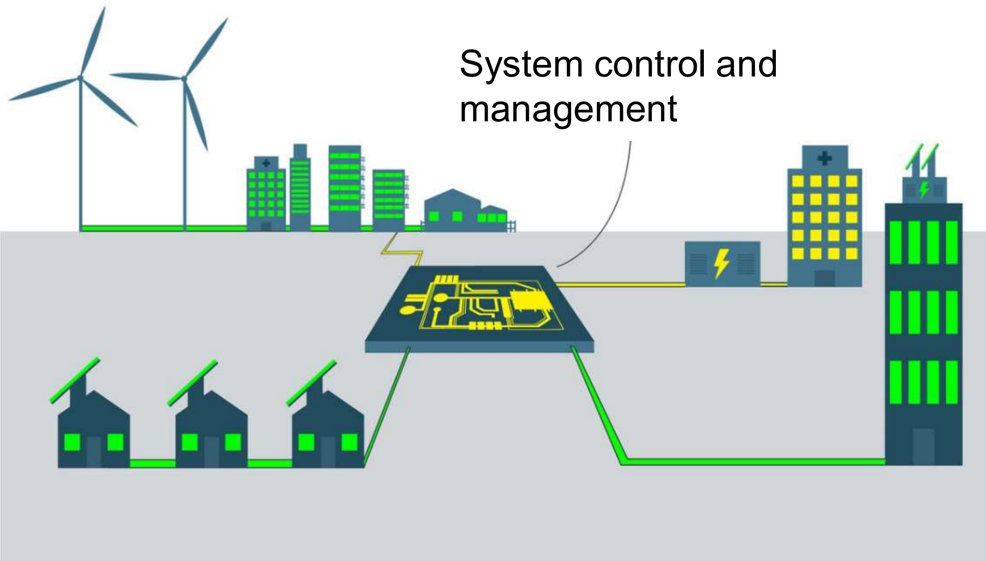


Source: Electric Power Research Institute, USA

Driving Forces of Change

Energy Security

- **Power Outages** *wreak havoc and cost billions of dollars in lost productivity and revenue.*
- ***Security Threats*** *are constant to the electric infrastructure. The physical and cyber security risks, from terrorists and hackers continue to grow exponentially.*
- **Aging Infrastructure**



Source: Electric Power Research Institute, USA

Driving Forces of Change

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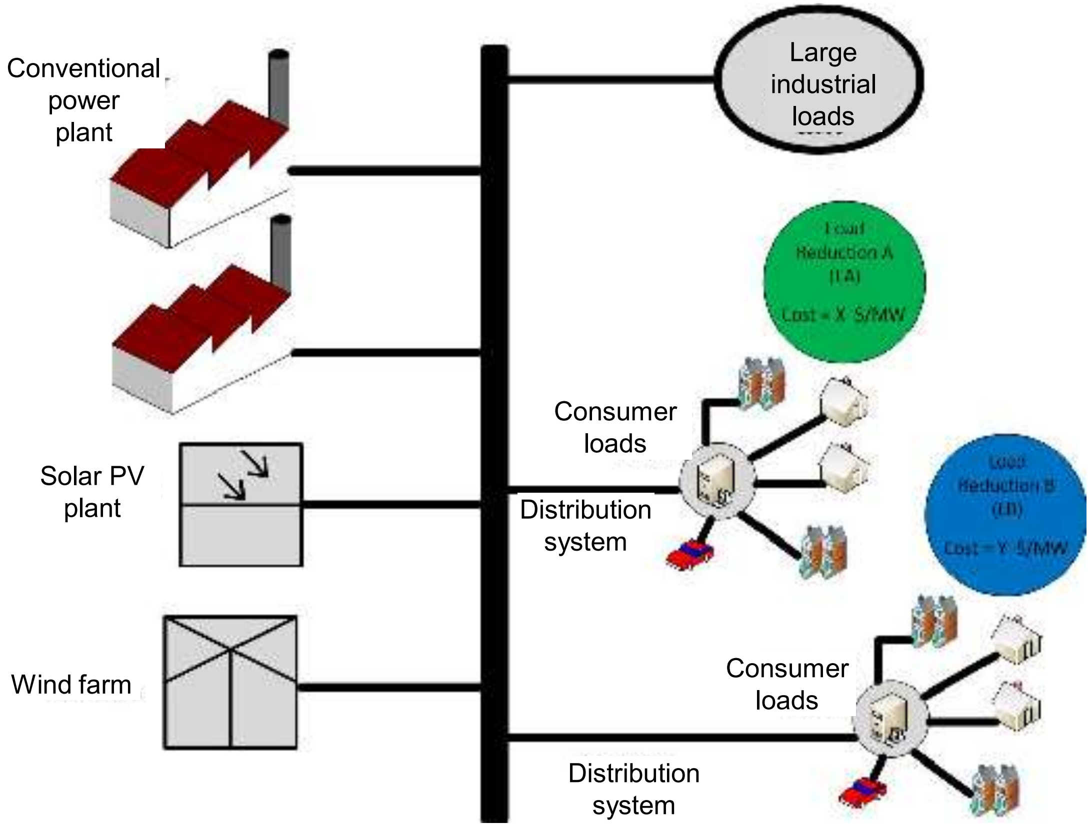
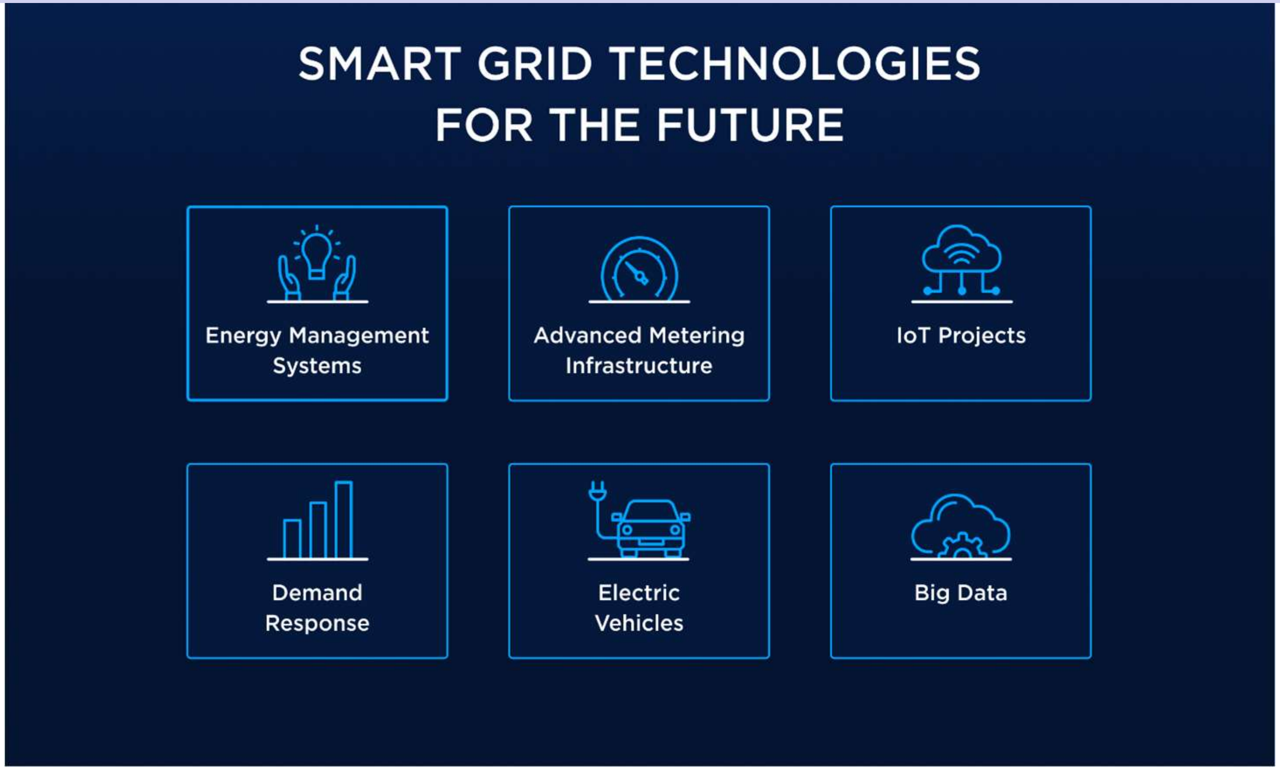


Source: Electric Power Research Institute, USA

Driving Forces of Change

Innovative Technology

- Holds significant promise as a “game changer.”
- Innovation is pervasive across the electricity value chain (from smart appliances to advanced energy storage technologies).



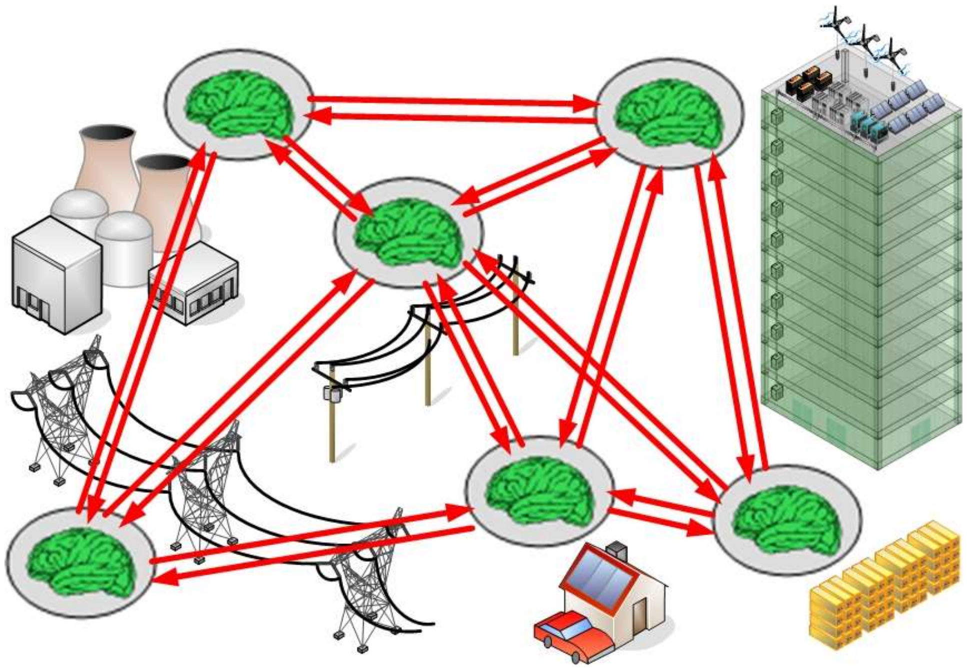
Source: Electric Power Research Institute, USA

So…
What is a Smart Grid?

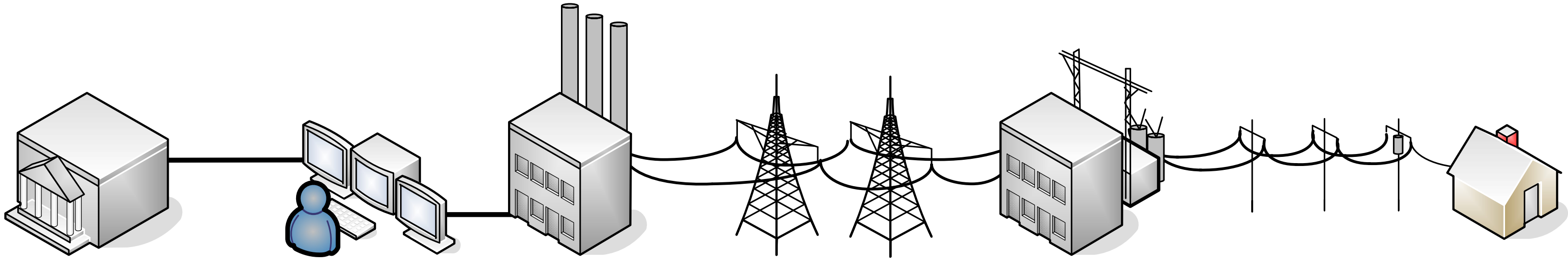
The smart grid concept

There are many views of what is a Smart Grid

In reality, a smart grid is not a single concept but rather a combination of technologies and methods intended to **modernize the existing grid** in order to **improve flexibility, availability, energy efficiency, and costs**.

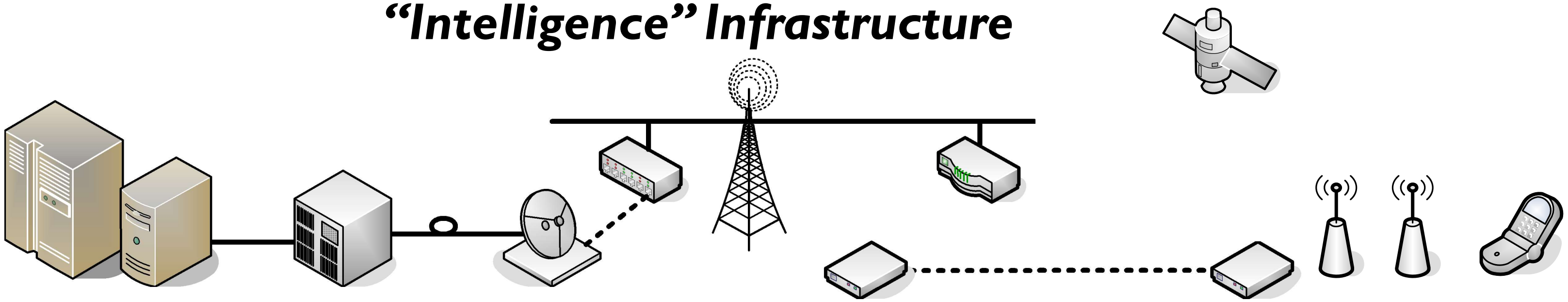


What does the concept of Smart Grid look like?



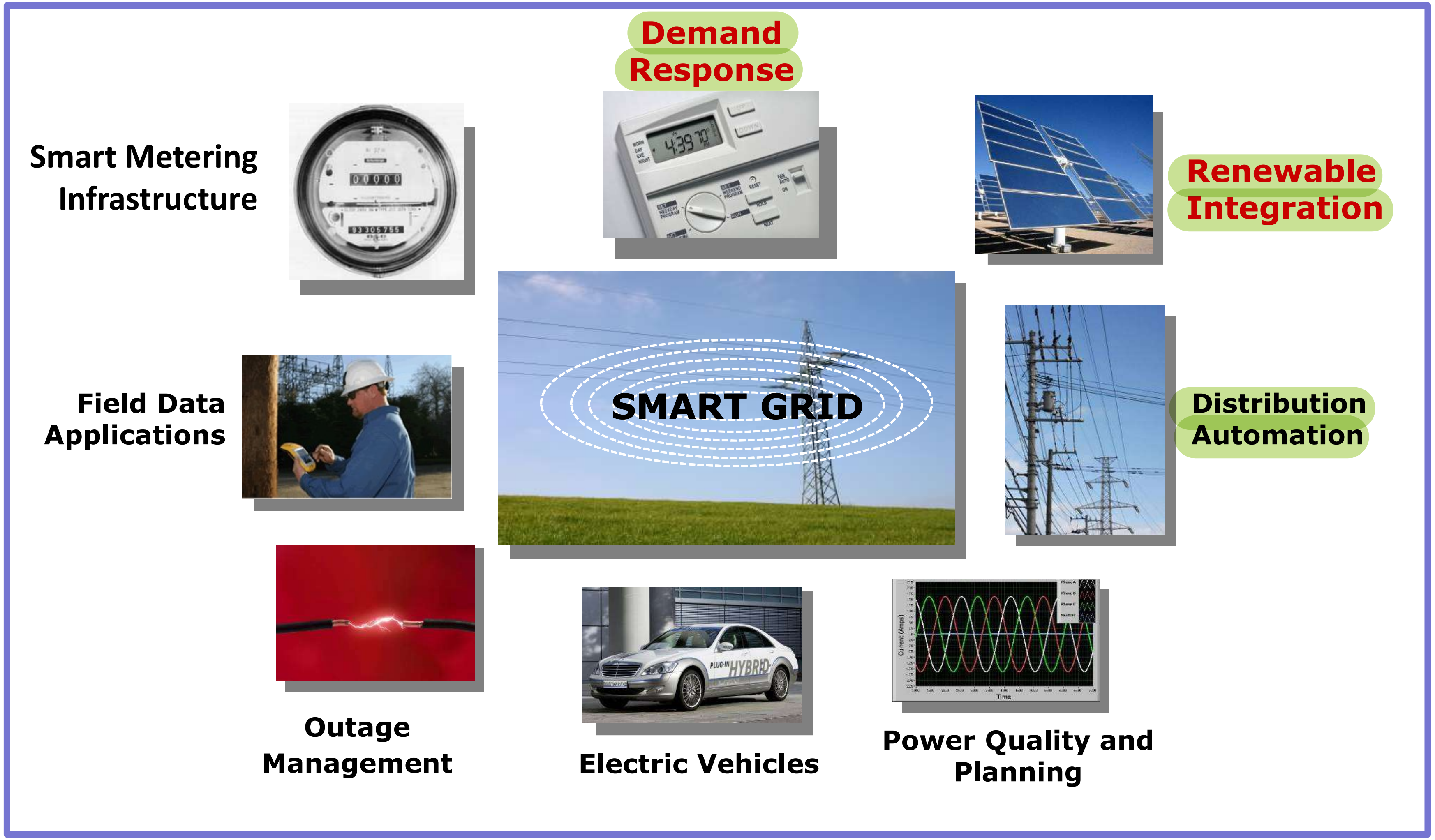
Electrical Infrastructure

"Intelligence" Infrastructure



Source: Electric Power Research Institute, USA

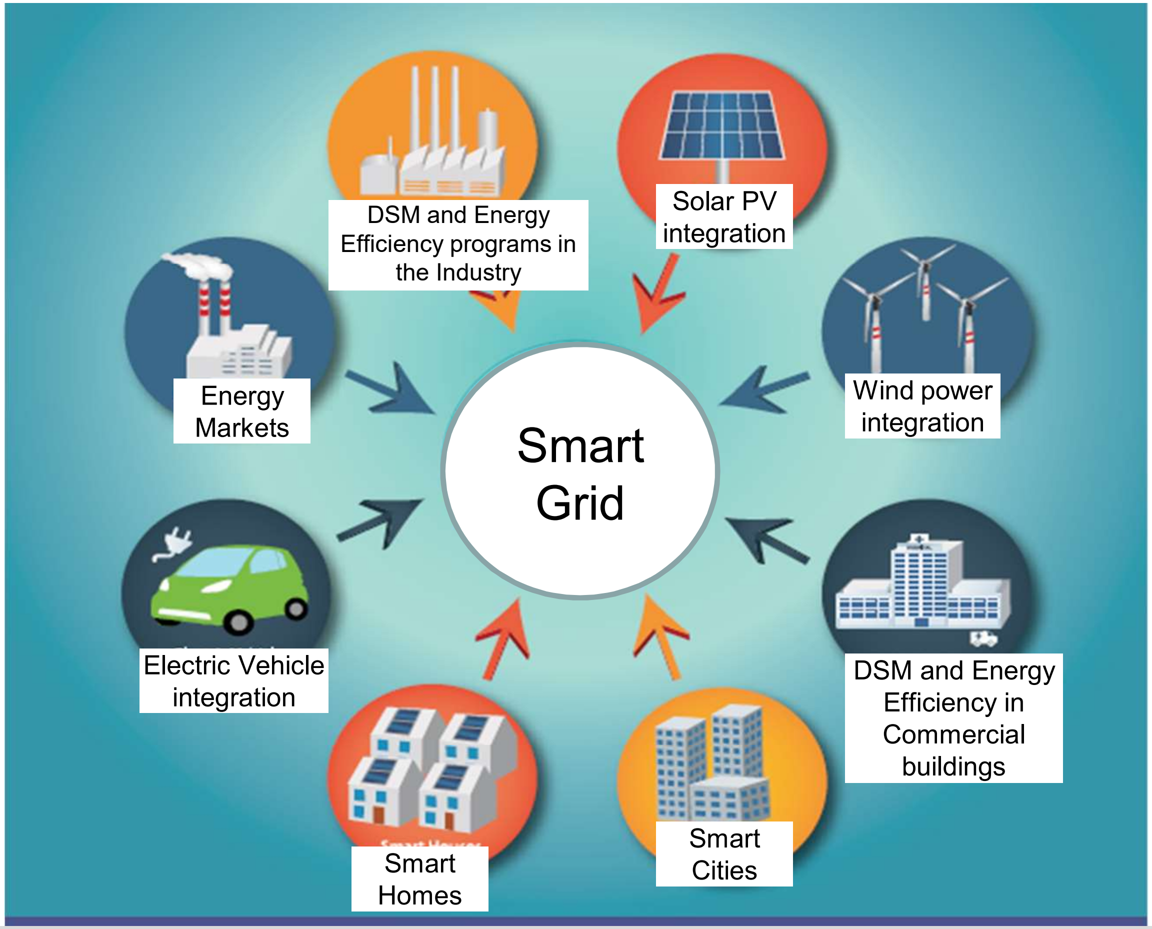
Smart Grid



Distributed Intelligence, Automated Controls, advanced sensing technologies, and Integrated Broadband Communications

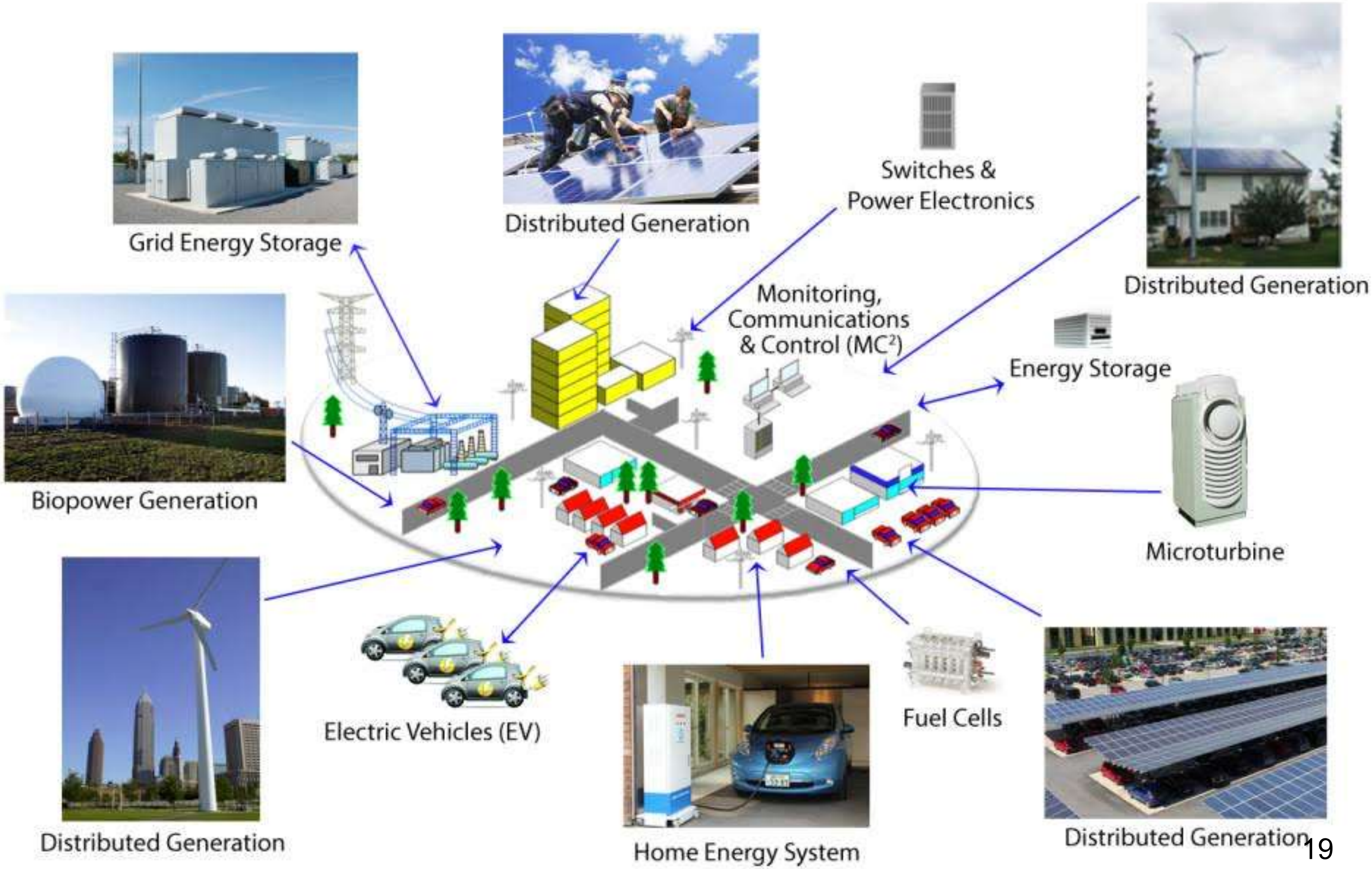
Source: Electric Power Research Institute, USA

Smart Grid: Enabler of the New Energy Economy



A Smart Grid will enable transition towards a sustainable energy future by improving energy efficiency, facilitating high integration of renewable energy sources and plug-in electric vehicles, enabling demand side management, and improving reliability

Smartgrid will have diverse generating sources with high percentage of renewables



Source: Electric Power Research Institute, USA

Value of a Smart Grid

Essentially, a Smart Grid can be defined as a broad range of solutions that optimize the energy value chain.

From an economic perspective:
A Smart Grid can enable reduced overall energy consumption through energy efficiency and demand response / load management programs.

From an environmental standpoint:
A Smart Grid can reduce carbon emissions by facilitating replacement of traditional forms of generation with renewable sources of generation, maximizing demand response / load management, minimizing use of peak generation

From power system perspective:
A Smart Grid holds the promise of improved efficiency, and enhanced reliability and security of the power system

Value of a Smart Grid

Parameter	Baseline	Business as usual (BAU)	Enhanced system with Smart Grid functionalities	Improvement over BAU
	(2010)	(2025)	(2025)	(2025)
Electricity Consumption (billion kWh)	4500	5800	4900-5200 10-15% ↓	10-15% reduction
% Demand Reduction at Peak	6%	15%	25%	66% increase
Carbon Dioxide Emissions (million metric tons of carbon)	680	900	720 20% ↓↓	20% reduction
Cost of Power Disturbances to Businesses (billions of dollars)	130	200	20 90% ↓↓	90% reduction (Smart Grids will also reduce the need for massive infrastructure investments by around $100 billion over the next 10 years)

Source: Electric Power Research Institute, USA

Value of a Smart Grid: Environmental Benefits

Implementing Smart Grid technologies could reduce carbon emissions by:

- Leveraging demand response to minimize the use of costly peaking generation, which typically uses generation that is comparatively fuel inefficient
- Facilitating increased energy efficiency through consumer education, programs leveraging usage information, and real-time pricing
- Facilitating mitigation of renewable generation variability of output—mitigation of this variability is one of the chief obstacles to integration of large amounts of renewable energy capacity into the bulk power system
- Integrating plug-in hybrid electric vehicles (PHEVs), distributed wind and photovoltaic solar energy resources, and other forms of distributed generation

Value of a Smart Grid: Benefits to Utilities

As utilities push for Smart Grid upgrades, they need to balance enhancement of advanced metering infrastructure, communication and other technologies while maintaining a reliable and safe infrastructure needed to serve their consumers.

- Improved Reliability
- Integration of Renewable Energy and Distributed Resources
- Deferred Capital Spending for Generation, Transmission, and Distribution Investments
- Reduced Operations and Maintenance Costs
- Increased Efficiency of Power Delivery

Value of a Smart Grid: Benefits to Consumers

Consumption Management

- Smart Grid technologies offer consumers the knowledge and ability to manage their own consumption habits through home/building automation.

Cost Savings from Peak Load Reduction

- Demand Side Management aimed at reducing peak load will have huge economic benefits for the utility and the consumer.

Cost Savings through Energy Efficiency

- Today's new smart metering and communication technology could enable consumers and system operators to monitor and potentially control consumption—and cost—at 15-minute intervals. Such improved awareness gives consumers incentives to reduce energy use by switching to more efficient appliances and light bulbs, adjusting thermostat temperatures, and turning off lights and other energy-consuming devices when not in use.

resell to grid

Convenience of Distributed Generation

- The new energy paradigm does not just empower utility consumers to better manage their consumption, reduce demand, and help the environment; through distributed generation, it can enable them to become energy producers.

Reduced Industrial Consumer Costs

- Commercial and industrial consumers will benefit greatly from all of the above programs

To appreciate the economic benefits, we need to first understand:

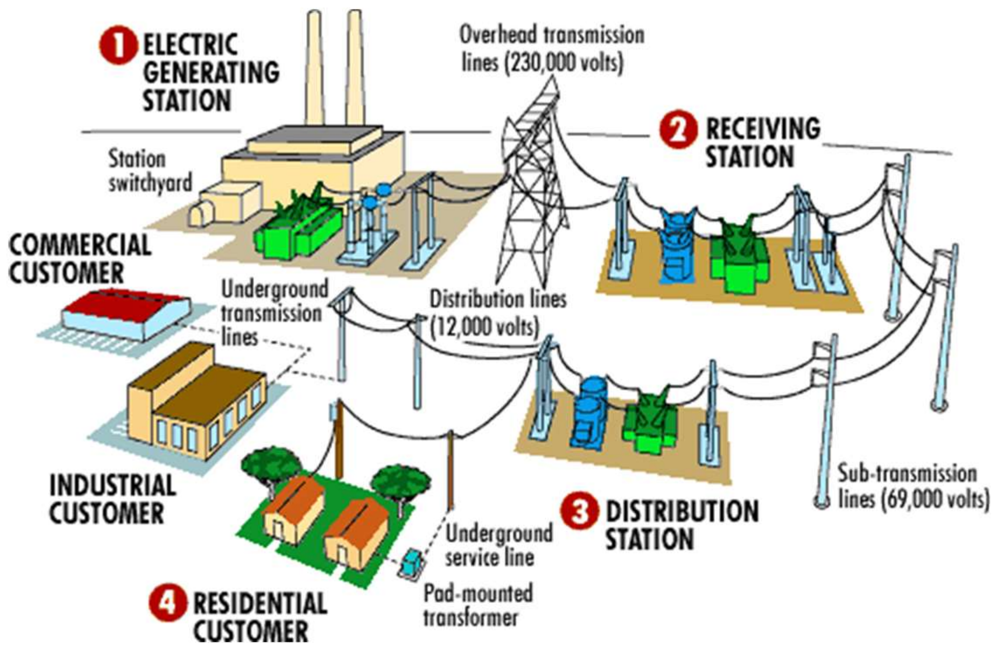
- Utility rate structure
- Energy economics
- Economics of renewable generation (Wind and Solar energy systems)
- Demand side management
- Energy efficiency

Refer to Chapter 5 of GM Master Book

Electricity Rate Structure and Billing

Demand Charge And Energy Charge

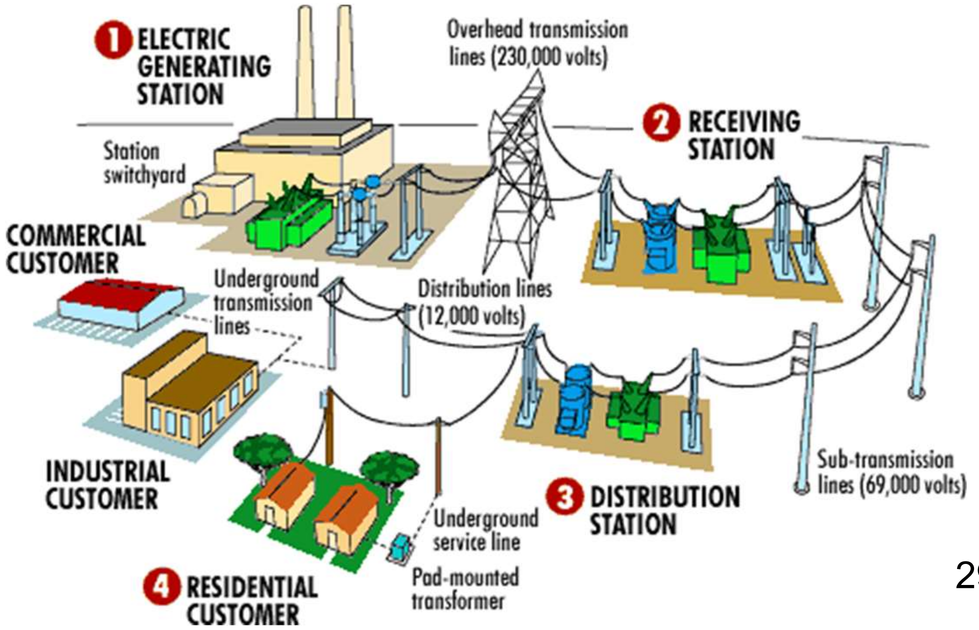
- Electric utilities really have two businesses: the electricity ***generating*** business and the electricity ***delivery*** business.
- **Energy charge** - based on the cost of generating or otherwise acquiring the energy itself:
  – fuel costs, for example, and the cost of purchasing electricity from another utility.



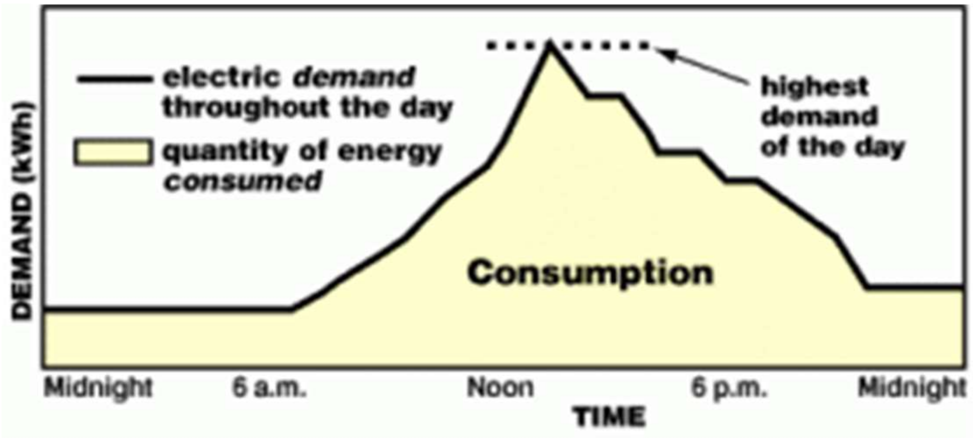
Demand Charge And Energy Charge

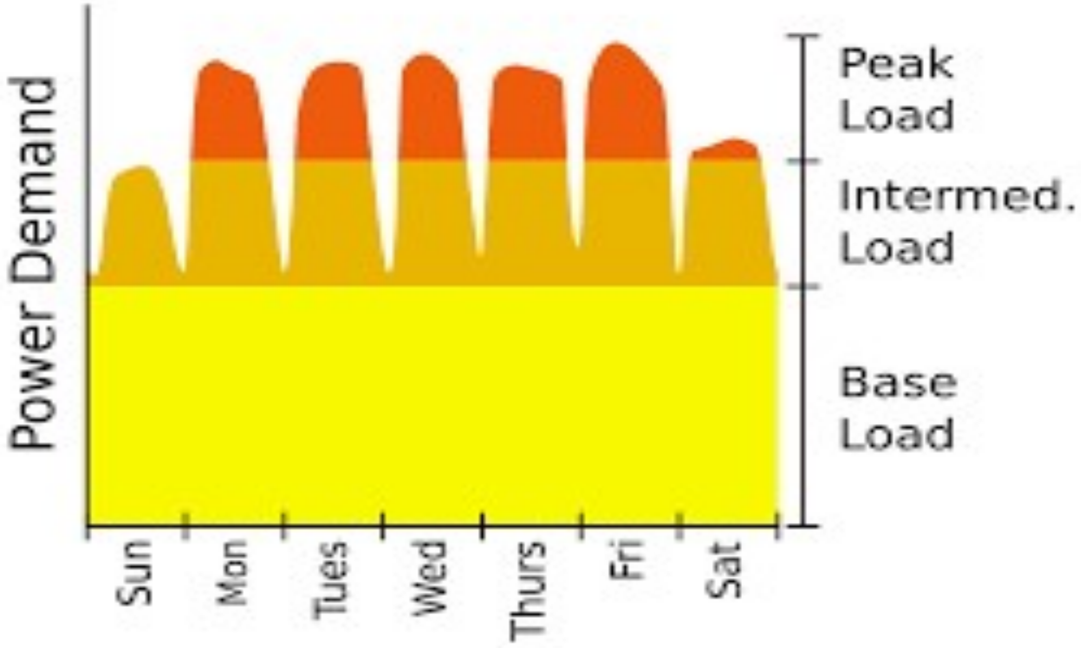
- **Demand charge** – deals with the delivery side of the business, with apportioning to each customer their fair share of the cost of building and maintaining the system of wires and transformers and other hardware needed to deliver the electrical energy they consume.
- Typically applied to commercial and industrial customers.
- Monthly demand charge.

- Based on Peak demand - the maximum kW that a facility draws from the system
- Irrespective of time of day the customer draws this power.



Electricity Rate Structure and Billing

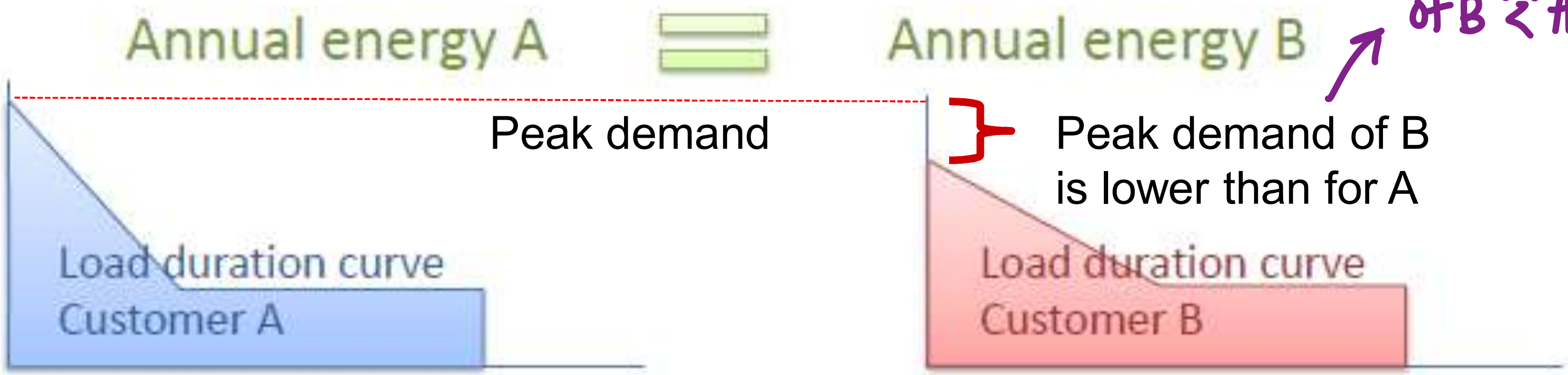




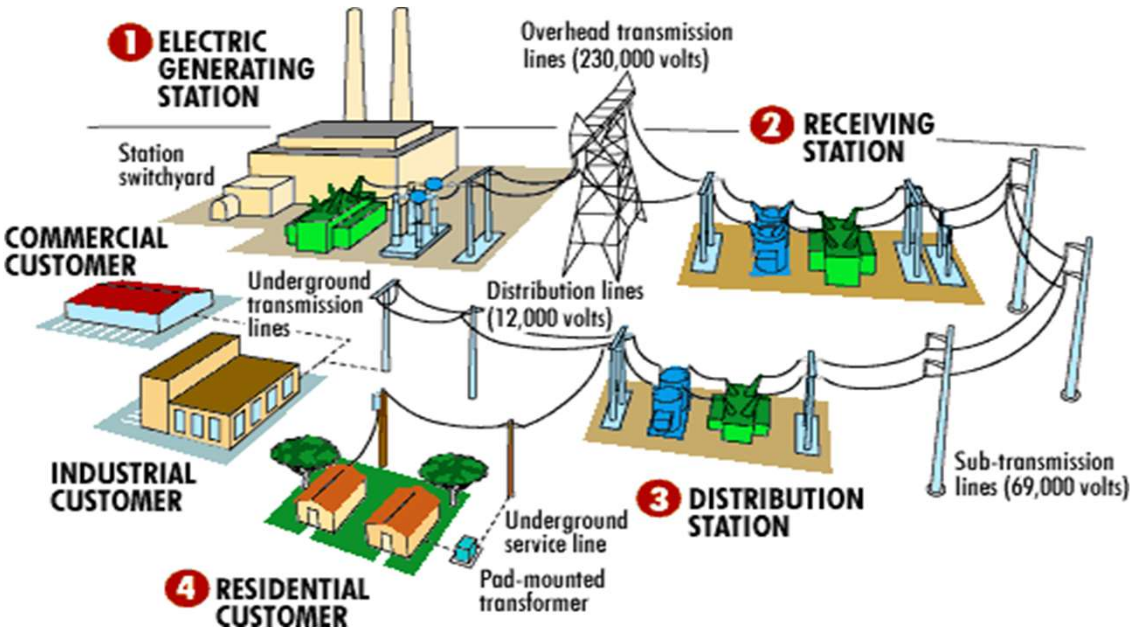
Electricity Rate Structure and Billing

DEMAND CHARGE AND ENERGY CHARGE

Energy demand of B < that of A



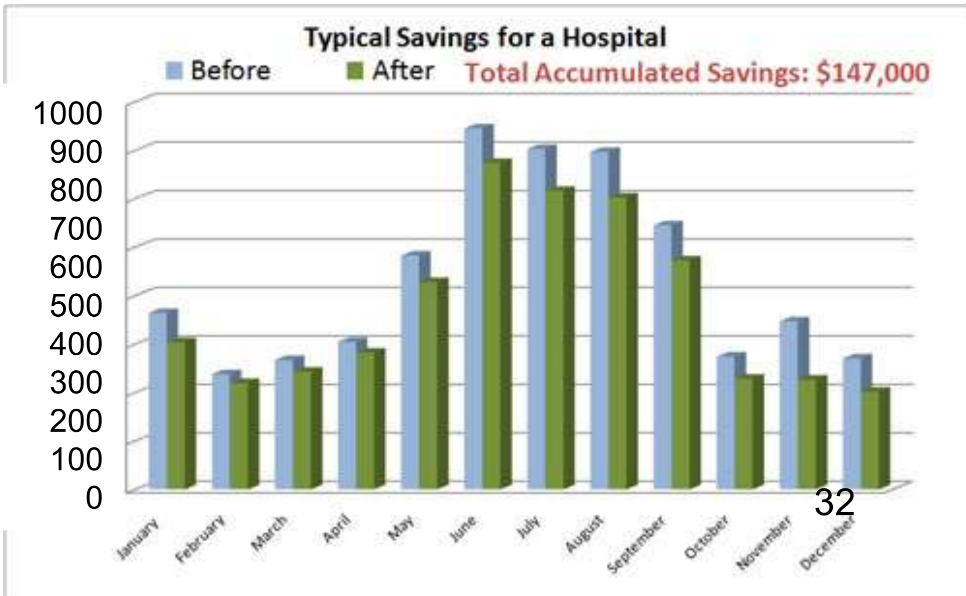
Energy production cost for A >>> Energy production cost for B



Ratcheted Demand Charges

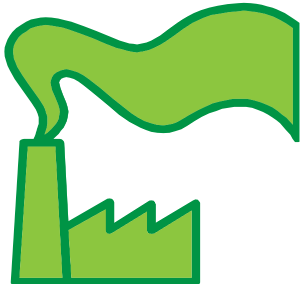
- Additional demand charge to the customers.
  - Account for the revenue of the peaking power plant. as a % of peak demand
  - Demand charges be ratcheted to a X% of annual peak demand
  - For example, if highest peak demand is 100 kW, every month the demand charges will be based on consumption of *at least X kW.*
- *If x = 80%, and once in the year, the consumer reaches a peak demand of 1000 kW,*
- *Then every month of the year, the demand charge will be based on consumption of at least 0.8 x 1000 = 800 kW*

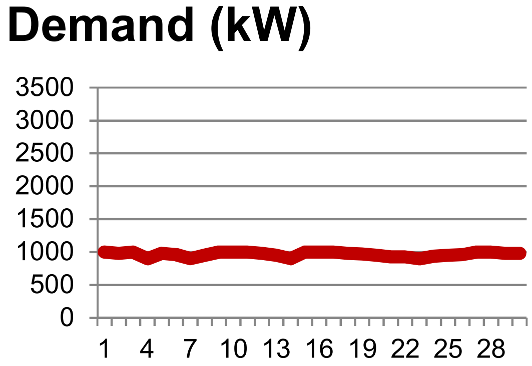
This can lead to heavy penalties for some customers



Tariff based on energy and demand

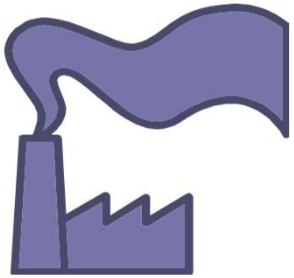
Factory A

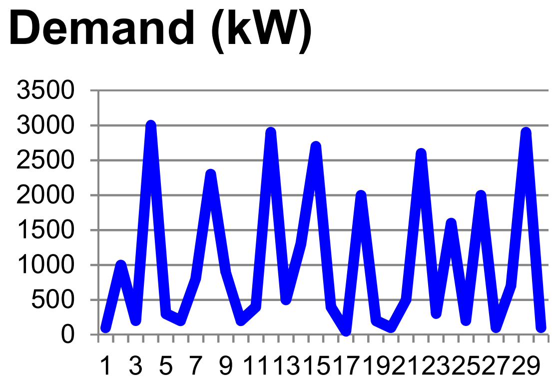




Operates at full load, night and day, constantly drawing 1000 kW
Total consumption in a month = 1000 kW x 720 h = 720,000 kWh

Factory B





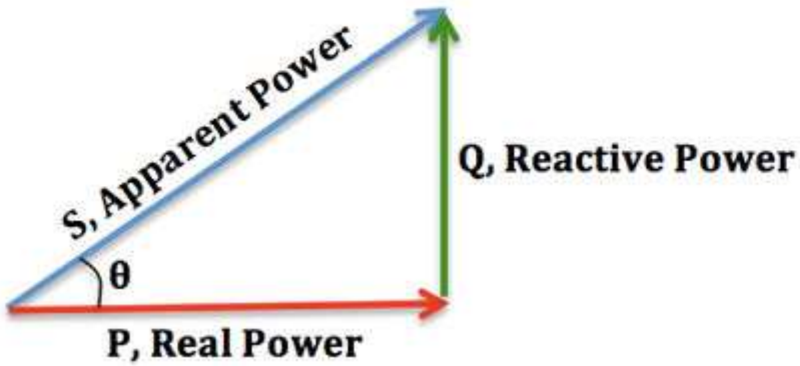
Draws same amount of energy, but load is continually changing.
Total consumption in a month = 720,000 kWh

↑ demand

Factory B should pay more for its energy!

Tariff based on power factor

- Power factor, which relates to "reactive power" or "kVAR," reflects the extent that current and voltage cycle in phase.



$$P = VI\cos\theta$$
$$= S\cos\theta$$

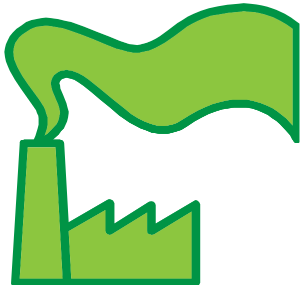
- Low power factor, such as that caused by a partly loaded motor, results in excessive current flow. Many electric utilities charge extra for low power factor because of the cost of providing the extra current.

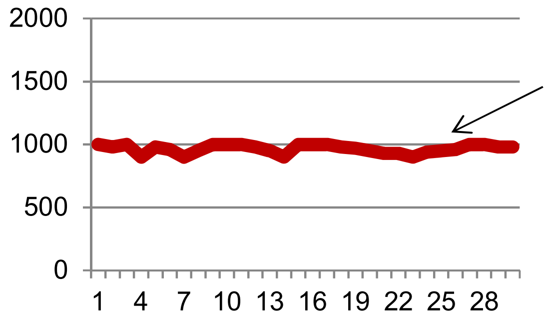
Tariff based on power factor

P = VI cos θ = S cos θ

Factory A

Operates at unity power factor

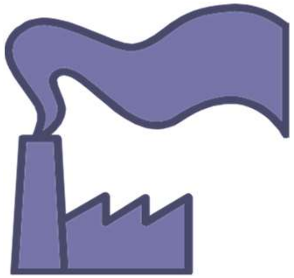


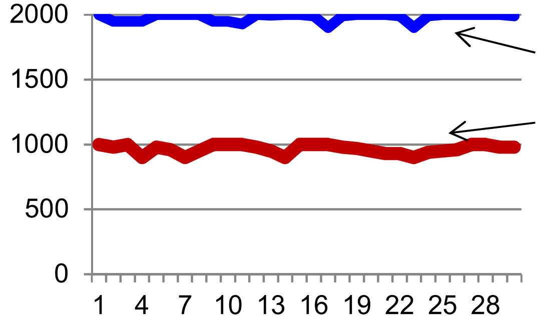


S = 1000kVA
P = 1000 kW

Factory B

Draws same amount of power, but has a power factor = 0.5





S = 2000kVA
P= 1000 kW

Factory B draws twice as much current, and should pay more!

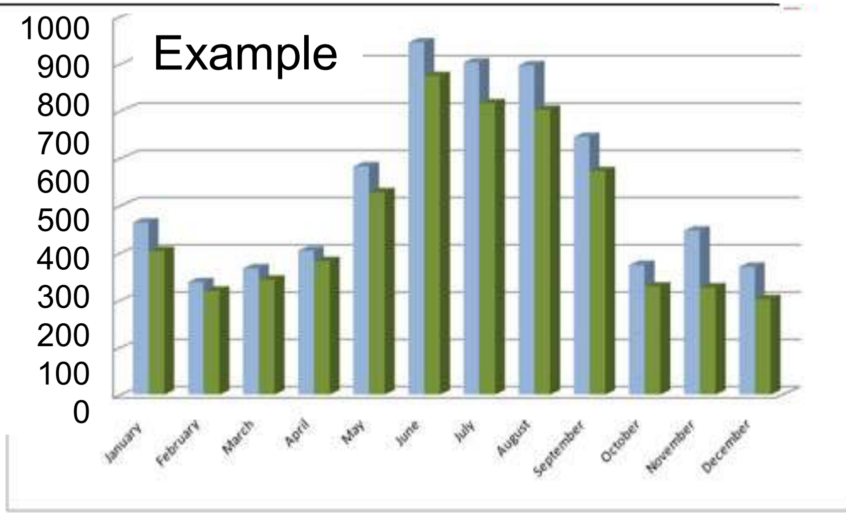
0.5 pf → 2 × I → 2 × $

Standard Residential Rates

- **Example : Standard Residential Electric Rate Schedule for a Utility**

Tier Level	Winter: November–April		Summer: May–October	
Tier I	First 620kWh	7.378¢/kWh	First 700kWh	8.058¢/kWh
Tier II	621–825	12.995¢/kWh	701–1000	13.965¢/kWh
Tier III	Over 825	14.231¢/kWh	Over 1000	15.688¢/kWh

Inverted block rate structure aims to discourage excessive consumption



Rate increase in summer to conserve during peak season

↑$, people try to save E to save $, ↓E consumed

New Rate Schedules

As the electrical industry is deregulated, many new pricing options will be offered.

Time-of-Use Rates

- "Time of use" is a model defining pricing in advance depending on different periods of the year and based on prior estimations of electric demand.

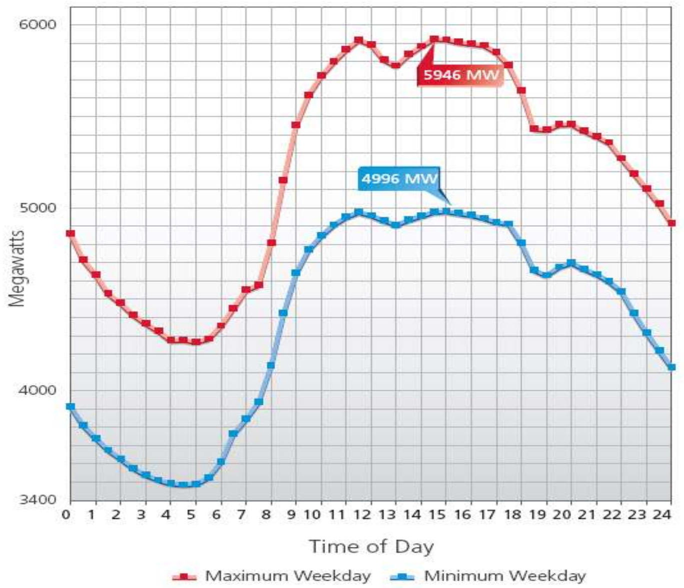
Real-time pricing

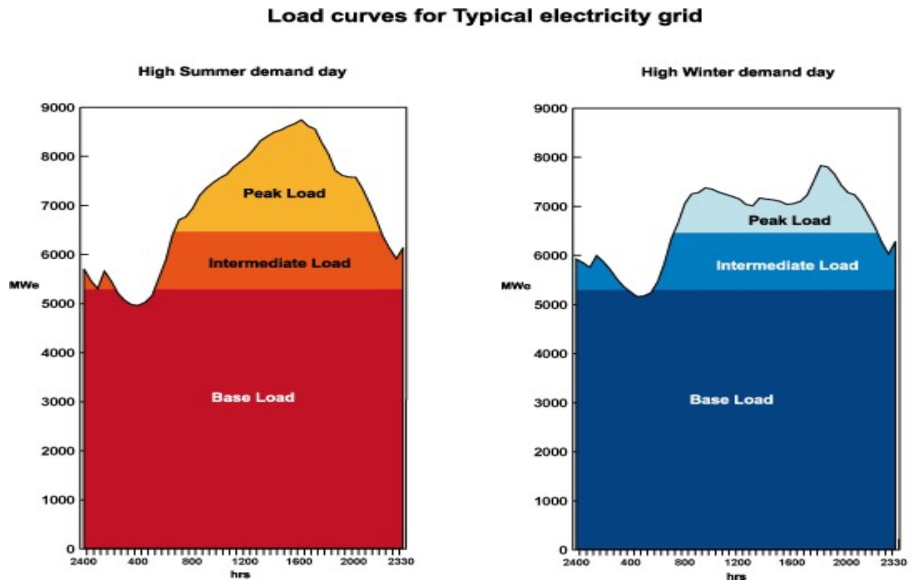
- where pricing varies continuously based on regional demand and block power

Rate Schedules

Time-of-Use Rates

- In most countries time-of-use rates, which favor off-peak electrical use, are available. ↗ ↑\$ at ↑demand, ↓\$ at ↓demand
- Encourage customers to shift load away from peak demand





↗ ∵ ↑demand means ↓supply

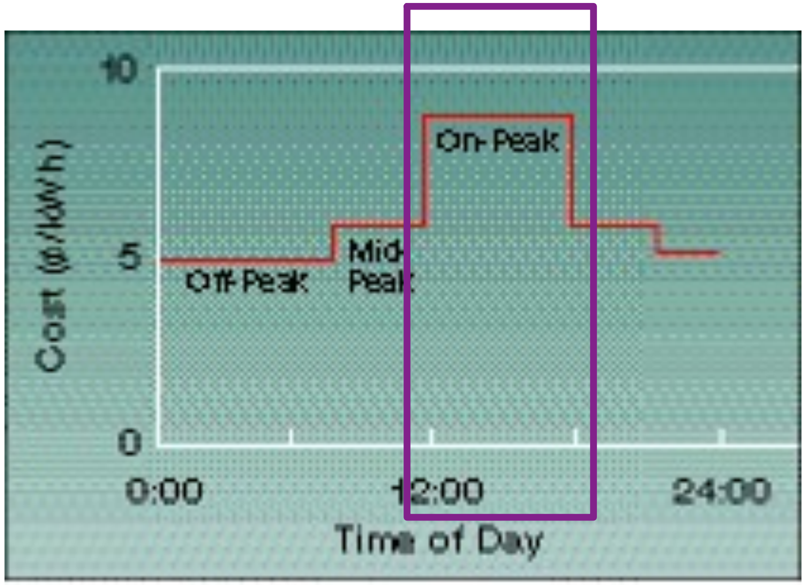
During peak-hours, it costs a lot more to generate electricity, hence customers should be charged more

Rate Schedules

Time-of-Use Rates

For example,

- Energy charges in summer from 9:30 pm – 8:30 am : **$0.05** /kWh
- Energy change from 8:30 am – 12:00 pm: **$0.06**/kWh
- Energy charge from 12- 6 pm: **$0.09**/kWh
- + demand change between 12-6 pm : **$10/kW**
- Energy change from 6 – 9:30 pm: **$0.06**/kWh



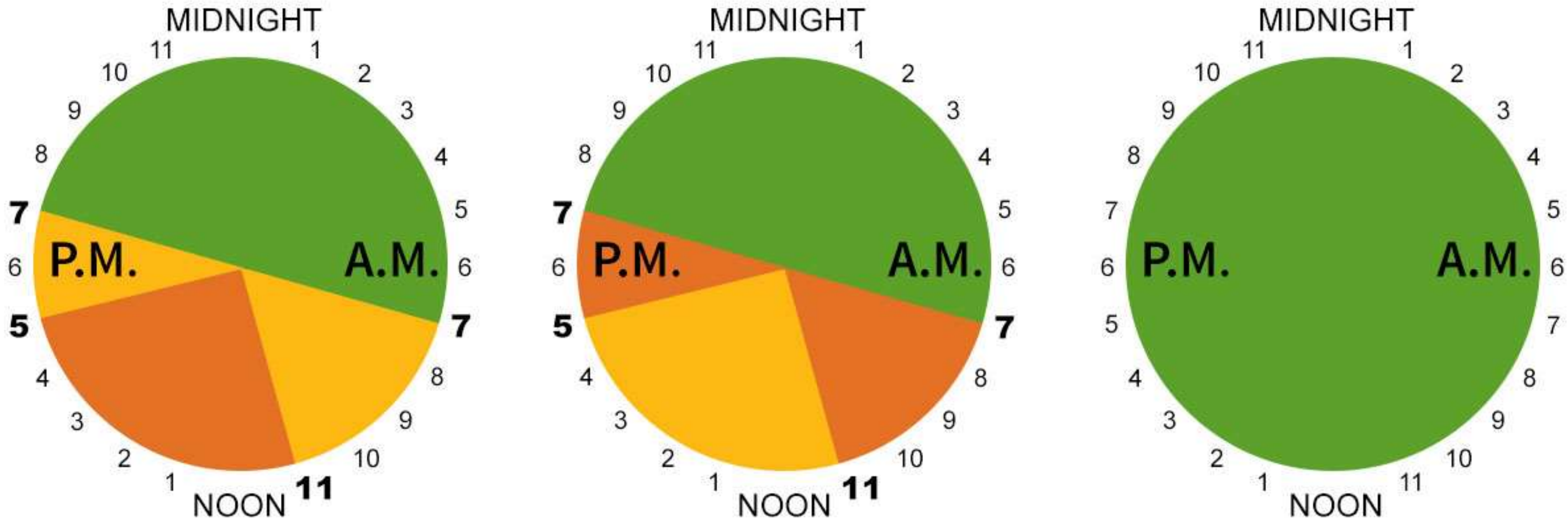
Typical Time-of-Use Rate Schedule

Example of TOU Rates

Summer - Weekdays
(May 1 - Oct 31)

Winter - Weekdays
(Nov 1 - Apr 30)

Weekends & Statutory Holidays

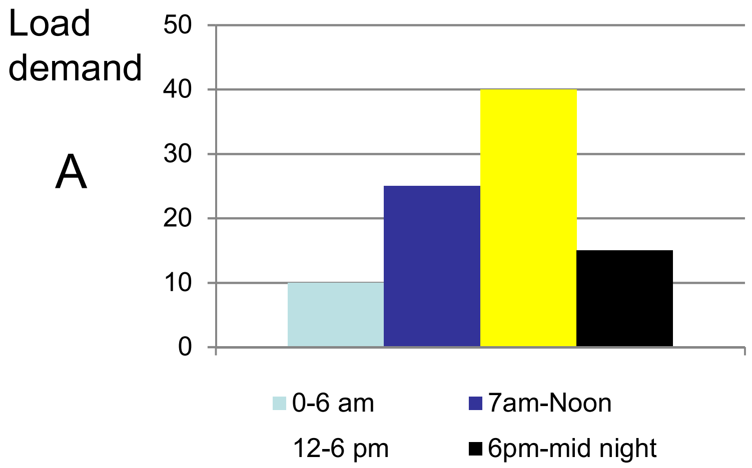


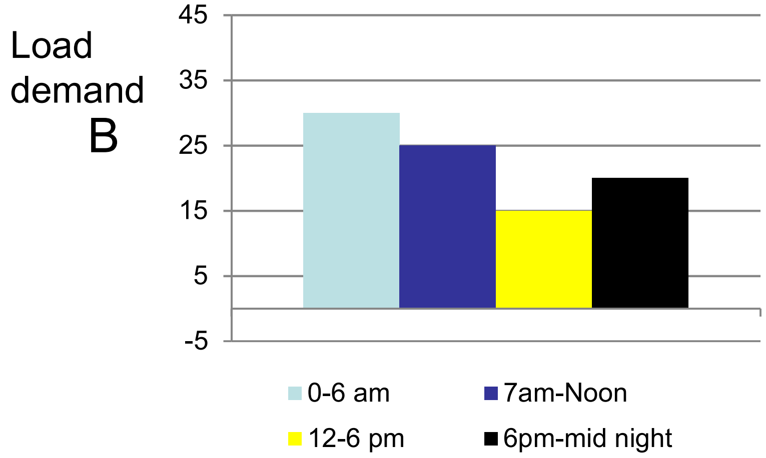
8.7¢ per kWh* — **Off-peak** Demand is lowest

13.2¢ per kWh* — **Mid-peak** Demand is moderate

18.0¢ per kWh* — **On-peak** Demand is highest

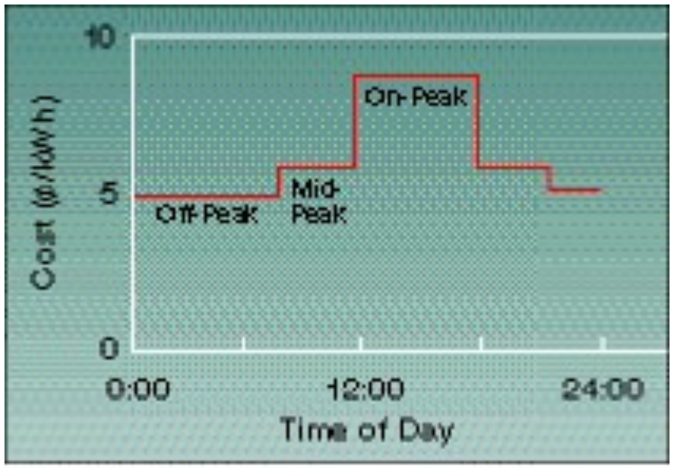
Time-of-Use (TOU) Rate





Energy production cost for A>>> Energy production cost for B

- Under the fixed rate structure, customer A pays same tariff as customer B.
- **New rate structure can incentivize customer A to shift its demand to off-peak hours.**



Typical Time-of-Use Rate Schedule

↳ instead of no. of hours, we charge by time of use!

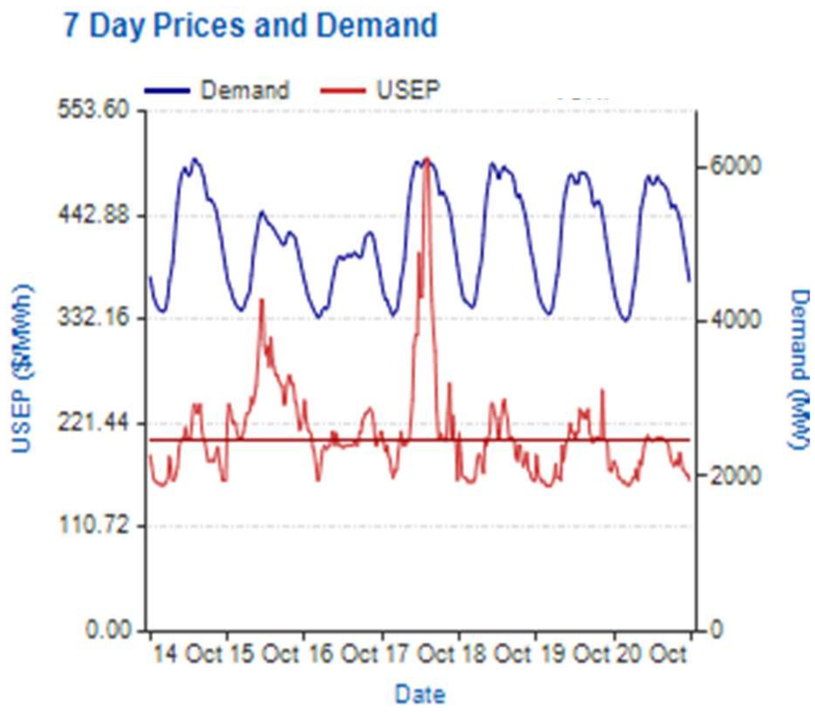
Real Time Pricing

Customer pays based on actual real-time fluctuating electricity price.

- Electricity prices may change as often as hourly.
- customers pay lower prices for electricity during off-peak hours, including nights and weekends.

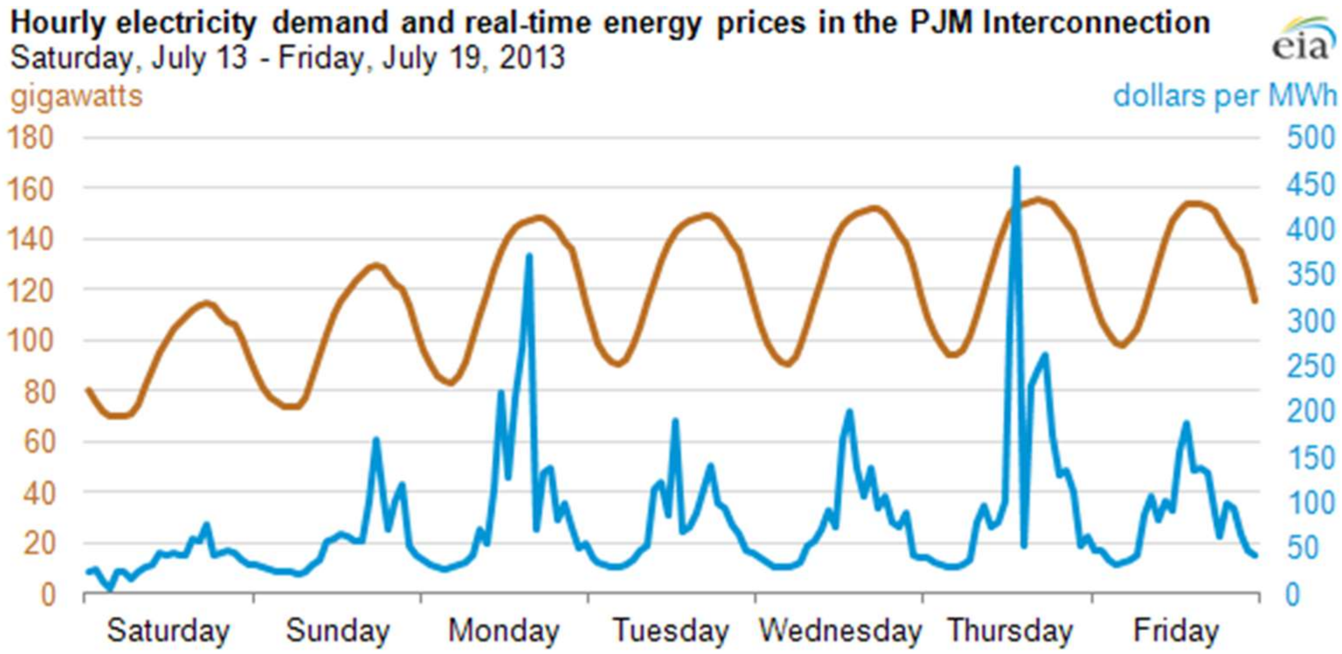
- Substantial potential savings obtained from using less electricity when electricity costs are high and shifting the use of power-hungry appliances to lower-priced hours

- Major efficiency improvements in the consumption and production of electric power.



USEP: Uniform Singapore Energy Price

Real Time Pricing



- Ideal rate structure.
- Real-time to reflect actual fluctuating electricity price.

- **Helps customers use electricity more efficiently**

Example 1

During the summer a rooftop PV system generates 10 kWh/day during the off-peak hours and 10 kWh/day during the on-peak hours. Suppose too, that the customer uses 2 kWh/day on-peak and 18 kWh/day off-peak. That is, the PVs generate 20 kWh/day and the household consumes 20 kWh/day. For a 30-day month in the summer, find the electric bill for this customer if the TOU rates shown below apply.

	PV supply	Demand
On-peak	10kWh	2kWh
Off-peak	10kWh	18kWh
Total	20kWh/day	20kWh/day

May–October	
2–8 P.M.	19.793 ¢/kWh
All other times	8.514 ¢/kWh

Example 1

	PV supply	Demand
On-peak	10kWh	2kWh
Off-peak	10kWh	18kWh
Total	20kWh/day	20kWh/day

May–October	
2–8 P.M.	19.793 ¢/kWh
All other times	8.514 ¢/kWh

During the on-peak hours, the customer generates 10 kWh and uses 2 kWh, so there would be a credit of :

10-2 => profit for 8kWh on-peak

On-peak credits = 8 kWh/day × \$0.19793/kWh × 30 day/mo

= \$47.50

During the off-peak hours, the customer generates 10 kWh and uses 18 kWh, so the bill for those hours would be:

10-18 => need pay for 8kWh off-peak

Off-peak bill = 8 kWh/day × \$0.08514/kWh × 30 day/mo

= \$20.43/mo

So the net bill for the month would be:

Net bill = \$20.43 − \$47.50 = −\$27.07mo

That is, the utility would owe the customer \$27.07 for this month.

What would be the 'net' bill, if the customer is charged the standard rate?

Energy Economics

to evaluate Investment in Renewable Generation, Energy Efficiency and Demand Side Management Programs

Refer to Chapter 5 of GM Master Book

Why Energy Economics?

DISTRIBUTED RESOURCES

DISTRIBUTED GENERATION

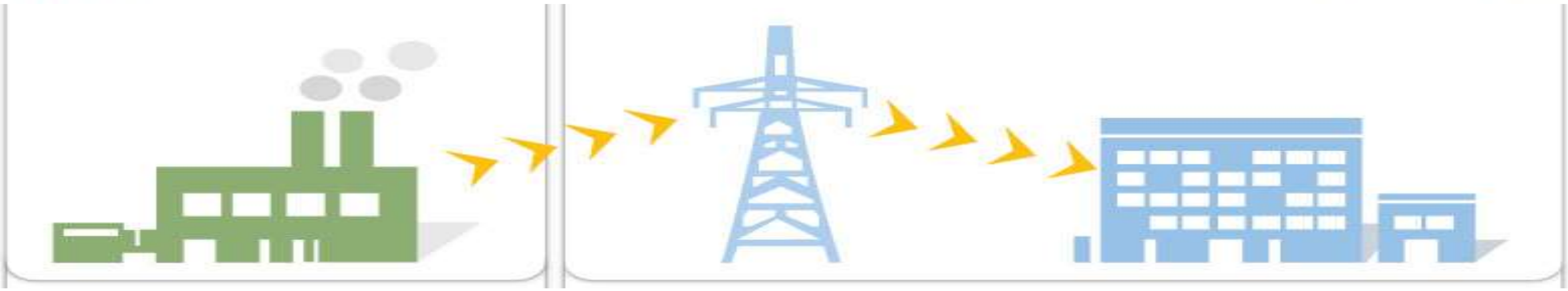
- Fuel cells
- Internal combustion engines
- Combustion turbines
- Biomass cogeneration
- Wind turbines
- Photovoltaics
- Mini-hydro

GRID RESOURCES

- Increased grid capacity
- Decreased grid losses
- Grid-sited storage
- Improved power factor
- Reduced connection losses
- Unaccounted for losses

DEMAND-SIDE RESOURCES

- Heat pumps
- Solar architecture
- Motor controls
- Efficient lighting
- Load shifting
- Appliance efficiency
- Absorption cooling



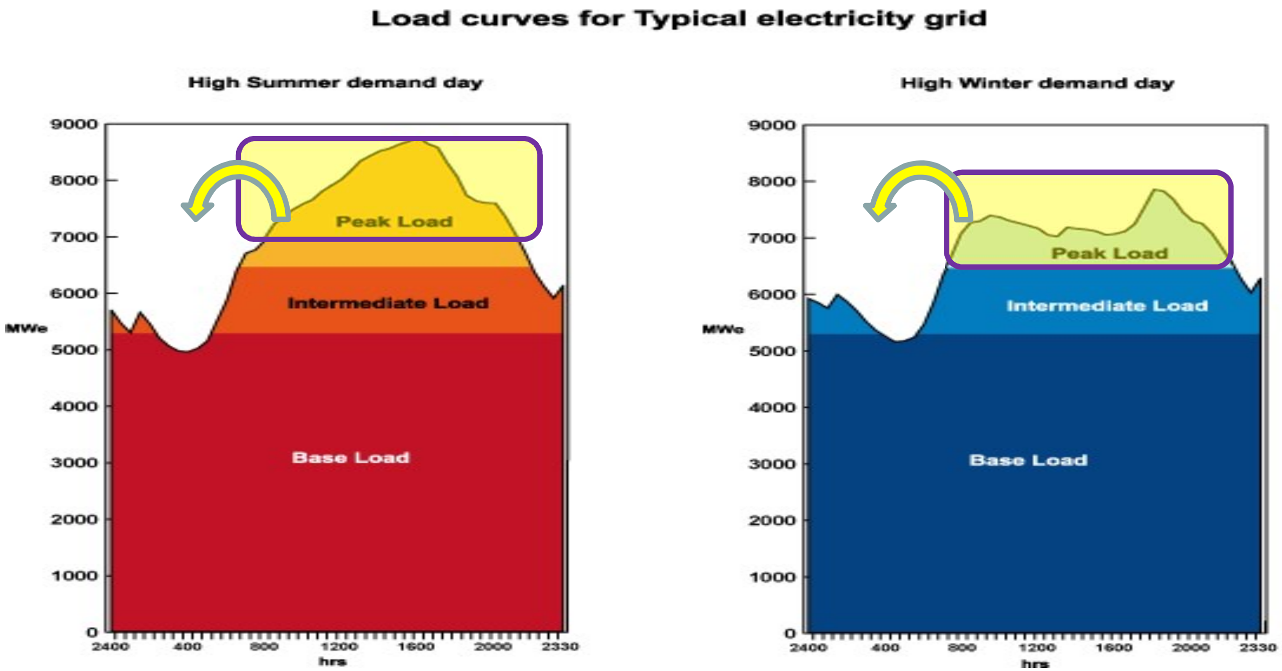
Cost analysis of DR project is a critical factor for investment.

Demand Side Management (DSM)

Demand Side Management (DSM)

Actions taken on customer side to change the amount or timing of energy consumption.

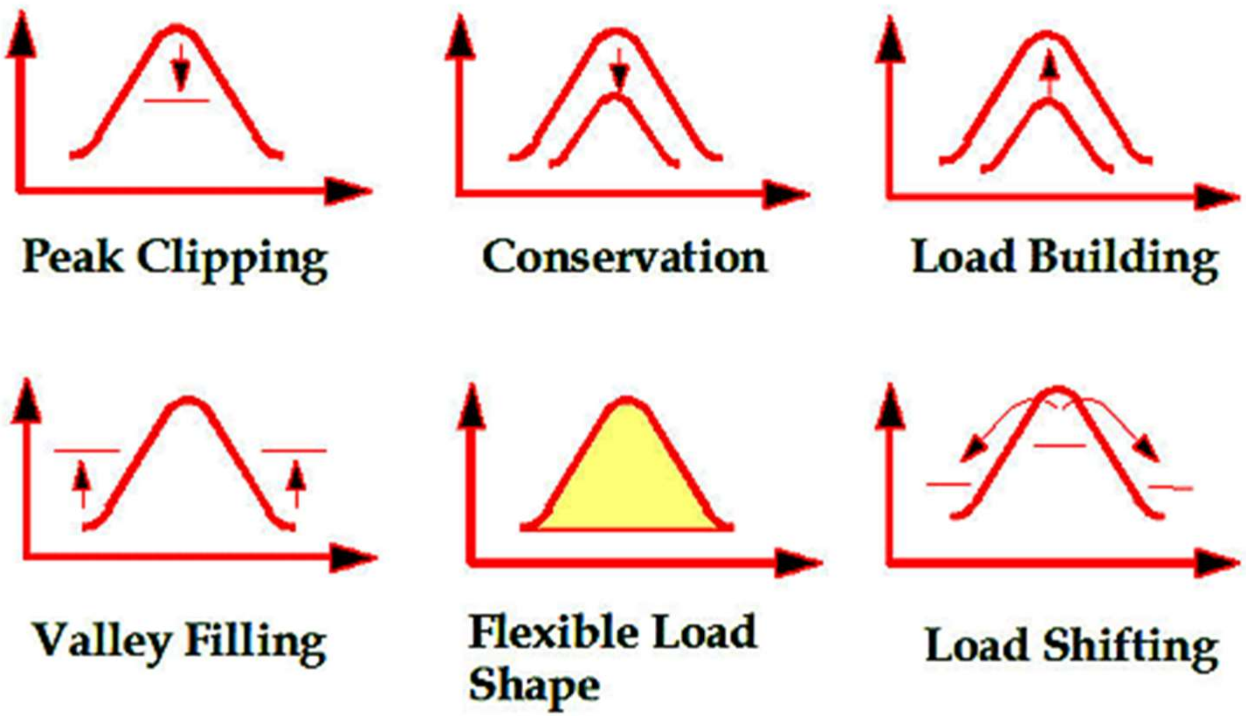
DSM strategies have the goal of maximizing end-use efficiency to avoid or postpone the construction of new generating plants.



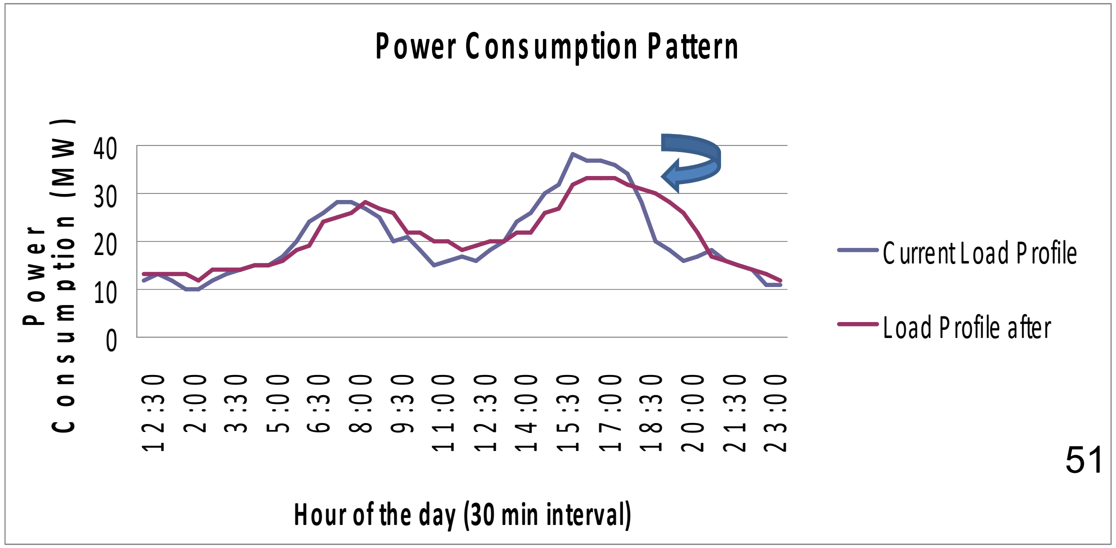
Focus is on shifting this peak load to off-peak regions

Demand Side Management – Load Management

Several strategies to alter the shape of the load demand curve:



DSM strategies reduce/shift the load at peak hours to off-peak hours:



Some basic concepts that will be useful for us to understand the economic benefits of these smart grid programs …

Simple Payback Period

- Simple measure to provide the time required for the return on investment.
- Extra first cost = investment ($).
- Annual savings = annual return ($/yr).

no. of years

$$\boxed{\text{Simple payback} = \frac{\text{Extra first cost } \Delta P(\$)}{\text{Annual savings } S(\$/\text{yr})}}$$

Example:

Initial cost of an energy efficiency project = $1000
Savings in electricity bill = $200/year
Simple payback = 5 years

- Pros: Simple to understand and calculate.
- Cons: Can be misleading. May make the investment look worse than it is.

Simple Rate-of-Return

- Inverse of simple payback period.
- Ratio of annual return to the investment. in /year.

$$\boxed{\text{Initial (simple) rate of return} = \frac{\text{Annual savings } S\ (\$/\text{yr})}{\text{Extra first cost } \Delta P\,(\$)}}$$

- Cons: May look much better than it actually is.
- Pros: Serves as minimum threshold.

- Note that both simple payback period and simple rate-of-return do not consider time value of money.

Future Value vs Present Value

Better

Future Value

- Translate current value to future value.

$$\boxed{F = P\,(1+i)^n}$$

  - P = current value
  - n = period (years)
  - F = future value
  - i = annual interest rate

Present Value

- Translate future value to equivalent present value.

$$\boxed{P = \frac{F}{(1+i)^n} \Rightarrow P = \frac{F}{(1+d)^n}}$$

  - P = current value
  - n = period (years)
  - F = future value
  - d = discount rate

↑ d, ↓ P_{value}

Discount rate can be considered as the interest earned from the best alternative investment option.

Higher discount rate → lower present value

Example 2

- Investment project saves $1000 in the 5th year.
- Best alternative investment earns 10%/yr.

Present worth: $P = \dfrac{F}{(1+d)^n}$

$$= \frac{\$1000}{(1+0.10)^5} = \$620.92$$

- Neutral between having $620.92 today or $1000 in the 5th year.

- Willing to spend as much as $620.92 today to save $1000 in the next 5 years.

Present Value Function

Since a distributed generation or efficiency investment will deliver financial benefits year after year, a conversion factor (called Present Value Function "PVF") can be used to find the **present value *P*** of a stream of annual cash flows *A*, for *n* years into the future, with a discount rate *d:*

$$P = A \cdot \mathrm{PVF}(d, n)$$

- Considers annual cash flow.
- All costs are represented as **fixed** 'annual' term.
- A is a stream of annual cash flows. (Each year invests $A)

Present Value Function

$$\boxed{P = A \cdot \text{PVF}(d, n)}$$

where PVF (d,n) is:

- If we invest $1 each year for n years,

$$\text{PVF}(d, n) = \frac{1}{1+d} + \frac{1}{(1+d)^2} + \cdots + \frac{1}{(1+d)^n}$$

1st year's PV   2nd year's PV ……….   nth year's PV

- PVF is summation of all present values.

$$\boxed{\text{PVF}(d, n) = \text{Present value function} = \frac{(1+d)^n - 1}{d(1+d)^n}}$$

*

(year)

Net Present Value (NPV)

- Present value of a project including all costs.
- Life-cycle cost (LCC) includes fixed and annual cost.
- The life-cycle cost (LCC) is used to compare investment options.

- Difference between investment options is called '**Net present value**' of the lower cost alternative.

NPV = LCC of product A – LCC of product B

sum of total costs of project in 1 year (including first costs)

Net Present Value (NPV)

- Alternatively, assume that the better product provides better savings (less annual cost) and higher first cost,

- Total present value of a project = present value of annual cost - added first cost of better project.

$$\boxed{\mathrm{NPV} = \Delta A \times \mathrm{PVF}(d, n) - \Delta P}$$

- *ΔA is the present value of all future savings*
- *ΔP is the additional initial cost*

Annual cost > 0

First cost > 0

added first costs/investments

Example 3

Two 100-hp electric motors are being considered: “good” and “premium.”

- The good motor draws 79 kW and costs \$2400; the premium motor draws 77.5 kW and costs \$2900.
- The motors run 1600 hours per year with electricity costing \$0.08/kWh.
- Over a 20-year life, find the net present value of the cheaper alternative when a discount rate of 10% is assumed.

Annual cost of each option:

$$A(\text{good}) = 79\ \text{kW} \times 1600\ \text{h/yr} \times \$0.08/\text{kWh} = \$10{,}112/\text{yr}$$

$$A(\text{premium}) = 77.5\ \text{kW} \times 1600\ \text{h/yr} \times \$0.08/\text{kWh} = \$9920/\text{yr}$$

Present value function when d = 0.1 and n = 20 years,

$$\text{PVF}(d, n) = \frac{(1+d)^n - 1}{d(1+d)^n}$$

$$= \frac{(1+0.10)^{20} - 1}{0.10(1+0.10)^{20}} = 8.5136\ \text{yr}$$

Example 3

first costs

The present value of the two motors, including first cost and annual costs, is therefore

$$P(\text{good}) = \$2400 + 8.5136 \text{ yr} \times \$10{,}112/\text{yr} = \$88{,}489$$
$$P(\text{premium}) = \$2900 + 8.5136 \text{ yr} \times \$9920/\text{yr} = \$87{,}354$$

The premium motor is the better investment with a net present value of

$$\text{NPV} = \$88{,}489 - \$87{,}354 = \$1{,}135$$

Internal Rate of Return (IRR) *

- **IRR is a discount rate that makes the NPV equal to zero.**
- It is used to compare investment options (>2 options).
- When NPV = 0, i.e. the investment is neutral, all investment options give the same return.
- The higher the IRR, the higher the profit!

↑ IRR, ↑ profits

$$\boxed{\mathrm{NPV} = \Delta A \times \mathrm{PVF}(\mathrm{IRR}, n) - \Delta P \quad = 0}$$

$$\mathrm{PVF}(\mathrm{IRR}, n) = \frac{\Delta P}{\Delta A} = \text{Simple payback period}$$

IRR allows the energy investment to be directly compared with the return that one might get for any other competing investment

– A persuasive measure!!

good for comparison !!!

How to Estimate IRR from PVF?

$$\text{PVF}(\text{IRR}, n) = \frac{\Delta P}{\Delta A} = \text{Simple payback period} \qquad \text{PVF}(d, n) = \frac{(1+d)^n - 1}{d(1+d)^n}$$

Life (years)	9%	11%	13%	15%	17%	19%	21%	23%	25%	27%	29%	31%	33%	35%	37%	39%
1	0.92	0.90	0.88	0.87	0.85	0.84	0.83	0.81	0.80	0.79	0.78	0.76	0.75	0.74	0.73	0.72
2	1.76	1.71	1.67	1.63	1.59	1.55	1.51	1.47	1.44	1.41	1.38	1.35	1.32	1.29	1.26	1.24
3	2.53	2.44	2.36	2.28	2.21	2.14	2.07	2.01	1.95	1.90	1.84	1.79	1.74	1.70	1.65	1.61
4	3.24	3.10	2.97	2.85	2.74	2.64	2.54	2.45	2.36	2.28	2.20	2.13	2.06	2.00	1.94	1.88
5	3.89	3.70	3.52	3.35	3.20	3.06	2.93	2.80	2.69	2.58	2.48	2.39	2.30	2.22	2.14	2.07
6	4.49	4.23	4.00	3.78	3.59	3.41	3.24	3.09	2.95	2.82	2.70	2.59	2.48	2.39	2.29	2.21
7	5.03	4.71	4.42	4.16	3.92	3.71	3.51	3.33	3.16	3.01	2.87	2.74	2.62	2.51	2.40	2.31
8	5.53	5.15	4.80	4.49	4.21	3.95	3.73	3.52	3.33	3.16	3.00	2.85	2.72	2.60	2.48	2.38
9	6.00	5.54	5.13	4.77	4.45	4.16	3.91	3.67	3.46	3.27	3.10	2.94	2.80	2.67	2.54	2.43
10	6.42	5.89	5.43	5.02	4.66	4.34	4.05	3.80	3.57	3.36	3.18	3.01	2.86	2.72	2.59	2.47
15	8.06	7.19	6.46	5.85	5.32	4.88	4.49	4.15	3.86	3.60	3.37	3.17	2.99	2.83	2.68	2.55
20	9.13	7.96	7.02	6.26	5.63	5.10	4.66	4.28	3.95	3.67	3.43	3.21	3.02	2.85	2.70	2.56
25	9.82	8.42	7.33	6.46	5.77	5.20	4.72	4.32	3.98	3.69	3.44	3.22	3.03	2.86	2.70	2.56
30	10.27	8.69	7.50	6.57	5.83	5.23	4.75	4.34	4.00	3.70	3.45	3.22	3.03	2.86	2.70	2.56

All values shown in the table is simple payback period with different project life ‘n’ (year), and internal rate of return ‘IRR’ (%/yr)

Example 4

Air condition costs extra 1000 but saves 200/yr., simple payback period = 5 yrs.

↳ payback $= \frac{P}{A} = \frac{1000}{200} = 5$ years

Life (years)	9%	11%	13%	15%	17%	19%	21%	23%	25%	27%	29%	31%	33%	35%	37%	39%
1	0.92	0.90	0.88	0.87	0.85	0.84	0.83	0.81	0.80	0.79	0.78	0.76	0.75	0.74	0.73	0.72
2	1.76	1.71	1.67	1.63	1.59	1.55	1.51	1.47	1.44	1.41	1.38	1.35	1.32	1.29	1.26	1.24
3	2.53	2.44	2.36	2.28	2.21	2.14	2.07	2.01	1.95	1.90	1.84	1.79	1.74	1.70	1.65	1.61
4	3.24	3.10	2.97	2.85	2.74	2.64	2.54	2.45	2.36	2.28	2.20	2.13	2.06	2.00	1.94	1.88
5	3.89	3.70	3.52	3.35	3.20	3.06	2.93	2.80	2.69	2.58	2.48	2.39	2.30	2.22	2.14	2.07
6	4.49	4.23	4.00	3.78	3.59	3.41	3.24	3.09	2.95	2.82	2.70	2.59	2.48	2.39	2.29	2.21
7	5.03	4.71	4.42	4.16	3.92	3.71	3.51	3.33	3.16	3.01	2.87	2.74	2.62	2.51	2.40	2.31
8	5.53	5.15	4.80	4.49	4.21	3.95	3.73	3.52	3.33	3.16	3.00	2.85	2.72	2.60	2.48	2.38
9	6.00	5.54	5.13	4.77	4.45	4.16	3.91	3.67	3.46	3.27	3.10	2.94	2.80	2.67	2.54	2.43
10	6.42	5.89	5.43	5.02	4.66	4.34	4.05	3.80	3.57	3.36	3.18	3.01	2.86	2.72	2.59	2.47
15	8.06	7.19	6.46	5.85	5.32	4.88	4.49	4.15	3.86	3.60	3.37	3.17	2.99	2.83	2.68	2.55
20	9.13	7.96	7.02	6.26	5.63	5.10	4.66	4.28	3.95	3.67	3.43	3.21	3.02	2.85	2.70	2.56
25	9.82	8.42	7.33	6.46	5.77	5.20	4.72	4.32	3.98	3.69	3.44	3.22	3.03	2.86	2.70	2.56
30	10.27	8.69	7.50	6.57	5.83	5.23	4.75	4.34	4.00	3.70	3.45	3.22	3.03	2.86	2.70	2.56

- Enter the row corresponding to project life, and move across until values close to the simple payback period, *P/A*, are reached.
- IRR is the interest rate in that column. For example, a 10-year project with a 5-year payback has an internal rate of return of just over 15%.

Example 4 (continued)

- The table for IRR can also be used to determine the IRR when the decision maker wants an energy payback, with interest, within a certain number of years.
- For example, in Example 3, the premium motor costs an extra $500 and saves $192/yr, giving it a simple payback period of:
- *P/A* = $500/$192 = 2.60 years.

Example 4 (continued)

- The table fo
the decision
within a cert

Life (years)	9%	11%	13%	15%	17%	19%	21%	23%	25%	27%	29%	31%	33%	35%	37%	39%
1	0.92	0.90	0.88	0.87	0.85	0.84	0.83	0.81	0.80	0.79	0.78	0.76	0.75	0.74	0.73	0.72
2	1.76	1.71	1.67	1.63	1.59	1.55	1.51	1.47	1.44	1.41	1.38	1.35	1.32	1.29	1.26	1.24
3	2.53	2.44	2.36	2.28	2.21	2.14	2.07	2.01	1.95	1.90	1.84	1.79	1.74	1.70	1.65	1.61
4	3.24	3.10	2.97	2.85	2.74	2.64	2.54	2.45	2.36	2.28	2.20	2.13	2.06	2.00	1.94	1.88
5	3.89	3.70	3.52	3.35	3.20	3.06	2.93	2.80	2.69	2.58	2.48	2.39	2.30	2.22	2.14	2.07
6	4.49	4.23	4.00	3.78	3.59	3.41	3.24	3.09	2.95	2.82	2.70	2.59	2.48	2.39	2.29	2.21
7	5.03	4.71	4.42	4.16	3.92	3.71	3.51	3.33	3.16	3.01	2.87	2.74	2.62	2.51	2.40	2.31
8	5.53	5.15	4.80	4.49	4.21	3.95	3.73	3.52	3.33	3.16	3.00	2.85	2.72	2.60	2.48	2.38
9	6.00	5.54	5.13	4.77	4.45	4.16	3.91	3.67	3.46	3.27	3.10	2.94	2.80	2.67	2.54	2.43
10	6.42	5.89	5.43	5.02	4.66	4.34	4.05	3.80	3.57	3.36	3.18	3.01	2.86	2.72	2.59	2.47
15	8.06	7.19	6.46	5.85	5.32	4.88	4.49	4.15	3.86	3.60	3.37	3.17	2.99	2.83	2.68	2.55
20	9.13	7.96	7.02	6.26	5.63	5.10	4.66	4.28	3.95	3.67	3.43	3.21	3.02	2.85	2.70	2.56
25	9.82	8.42	7.33	6.46	5.77	5.20	4.72	4.32	3.98	3.69	3.44	3.22	3.03	2.86	2.70	2.56
30	10.27	8.69	7.50	6.57	5.83	5.23	4.75	4.34	4.00	3.70	3.45	3.22	3.03	2.86	2.70	2.56

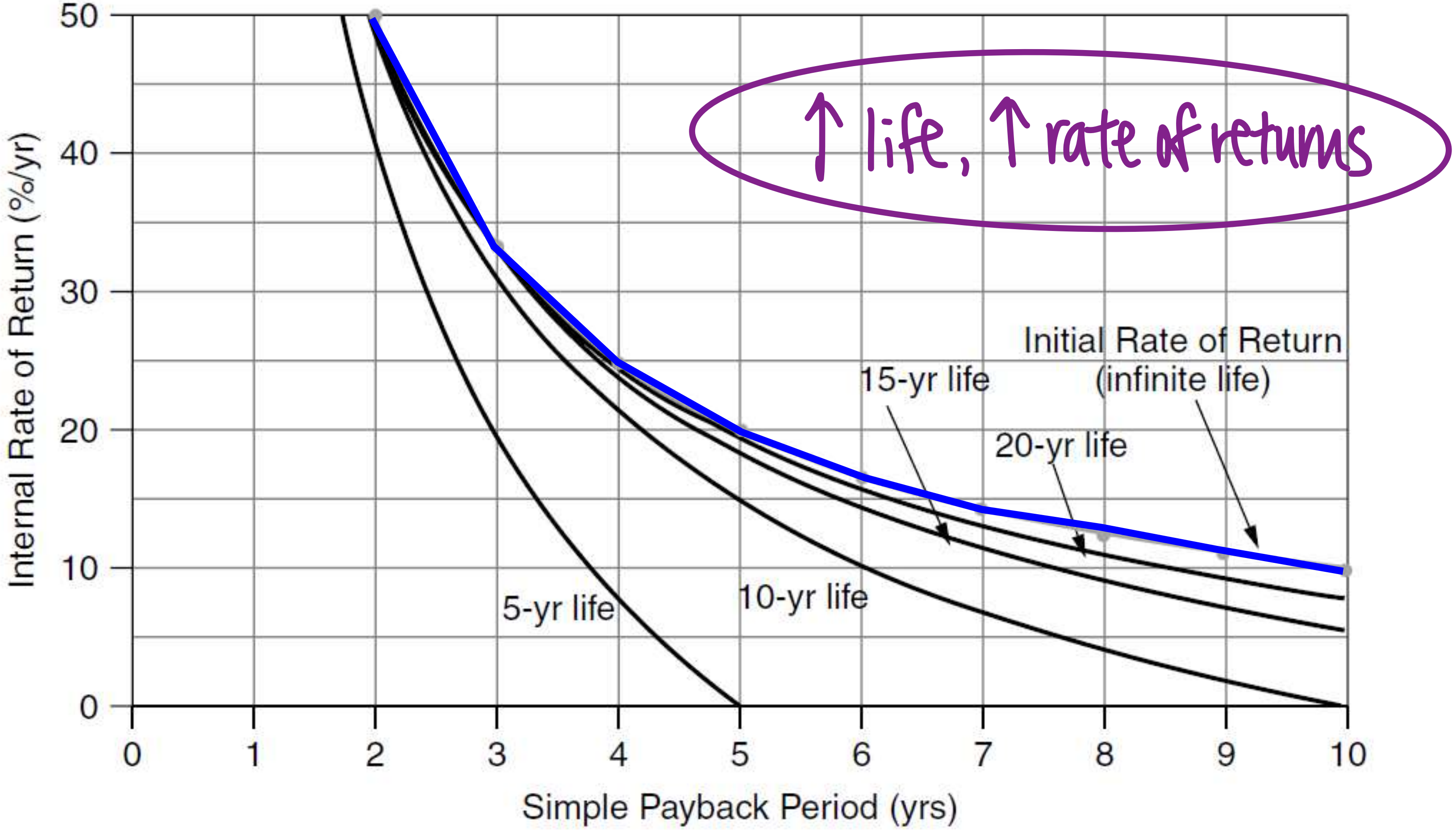
- Assuming a 20-year life and using the table, the internal rate of return is : 38.34%

life = 5 years!!

- Suppose management decides that it wants to earn all of its extra $500 investment (with interest) back in 5 years,
- That is equivalent to saying the efficiency device has only a 5-year life.
- From the table, the investment would still earn, almost 27% compounded annual interest.

IRR vs Project Life

- Figure below can be used to translate payback into the more persuasive internal rate of return.
- Same simple payback period, longer project life gives better interest!!



PVF with Fuel Escalation

- **Since fuel costs are generally increasing over the years, the amount of money saved by DG or efficiency measure will increase in time**
- Previously, all costs were represented as **fixed** 'annual' terms.
- Year 0, no fuel escalation.
- If we invest $1 each year for n years,

$$\frac{1}{1+d} + \frac{1}{(1+d)^2} + \cdots + \frac{1}{(1+d)^n}$$

1st year's PV — In the 1st year, the cost may be higher, say 1+e

2nd year's PV — In the 2nd year, the cost will be $(1+e)^2$

nth year's PV — In the nth year, the cost will be $(1+e)^n$

e is the escalation rate of annual savings

$$\mathrm{PVF}(d, e, n) = \frac{1+e}{1+d} + \frac{(1+e)^2}{(1+d)^2} + \ldots + \left(\frac{1+e}{1+d}\right)^n$$

We had previously found:

$$\mathrm{PVF}(d, n) = \frac{1}{1+d} + \frac{1}{(1+d)^2} + \cdots + \frac{1}{(1+d)^n}$$

$\boxed{d'}$

IRR with Fuel Escalation

- Use equivalent discount rate with fuel escalation.

$$\frac{1+e}{1+d} = \frac{1}{1+d'} \Rightarrow \boxed{d' = \frac{d-e}{1+e}}$$

To find the IRR when there is fuel escalation, the present value of the escalating series of annual savings must equal the extra initial principal,

NPV = ΔAxPVF(d', n) - ΔP = 0

$$\mathrm{PVF}(d', n) = \frac{\Delta P}{\Delta A} \xrightarrow{\text{Find IRR}} \mathrm{IRR}_0 = \frac{d-e}{1+e}$$

IRR_0 is the internal rate of return without fuel escalation

Actual IRR with fuel escalation:

$$\underset{(d)}{\mathrm{IRR}_e} = \underset{(d')}{\mathrm{IRR}_0}(1+e) + e$$

IRR_e is the internal rate of return with fuel escalation

Example 5

The premium motor in Example 3 costs an extra \$500 and saves \$192/yr at today's price of electricity. If electricity cost rises at an annual rate of 5%, find the net present value of the premium motor if the best alternative investment earns 10%.

- The equivalent discount rate with fuel escalation is

$$d' = \frac{d-e}{1+e} = \frac{0.10-0.05}{1+0.05} = 0.04762$$

- the present value function for 20 years of escalating savings is

$$\mathrm{PVF}(d', n) = \frac{(1+d')^n - 1}{d'(1+d')^n}$$

$$= \frac{(1+04762)^{20} - 1}{0.04762(1+0.04762)^{20}} = 12.717 \text{ yr}$$

- the net present value:

$$\mathrm{NPV} = \Delta A \times \mathrm{PVF}(d', n) - \Delta P$$

$$= \$192/\text{yr} \times 12.717 \text{ yr} - \$500 = \$1942$$

This is much higher than the NPV without fuel escalation (\$1135)

↳ duh... because fuel \$↑↑...

Annual Payment

- Rewrite the equation as,

$$A = P \times \mathrm{CRF}(i, n)$$

- CRF is a Capital recovery factor (/yr), which is an inverse of present value function (PVF).
- We can use it to find the annual payments to the loan.

$$\mathrm{PVF}(d, n) = \text{Present value function} = \frac{(1+d)^n - 1}{d(1+d)^n}$$

$$\boxed{\mathrm{CRF}(i, n) = \text{Capital recovery factor}(\mathrm{yr}^{-1}) = \frac{i(1+i)^n}{(1+i)^n - 1}}$$

(i = interest rate (%/yr))

Capital recovery factor (CRF) is used to convert the total loan to annualized payment.

Annualized Investment

- Typically, the capital required for investment comes from a loan.
- Requires a series of equal annual payments to pay off the loan with interest.
- From present value function,

Can be thought of as "Principal" borrowed ($)

$$\boxed{P} = \boxed{A} \cdot \mathrm{PVF}(d, n)$$

Loan terms (yrs)

Annual payments to pay off the loan ($) Interest rate (%/yr)

How much do we need to pay off the loan in each year?
→ What is A?

PVF vs CRF

Annualized Investment

- Present value function (PVF) is used to convert the annualized budget to the total budget.

$$\boxed{P = A \cdot \mathrm{PVF}(d, n)}$$

  - P = total budget
  - A = annualized budget
  - n = period (years)
  - d = annual discount rate

Annual Payment

- Capital recovery factor (CRF) is used to convert the total loan to annualized payment.

$$\boxed{A = P \times \mathrm{CRF}(i, n)}$$

  - P = total budget
  - A = annualized budget
  - n = period (years)
  - i = annual interest rate

CRF is the reciprocal of PVF.

CRF vs Loan Terms and Interest Rate

Interest rate

Loan term

Years	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%
5	0.2184	0.2246	0.2310	0.2374	0.2439	0.2505	0.2571	0.2638	0.2706	0.2774	0.2843
10	0.1172	0.1233	0.1295	0.1359	0.1424	0.1490	0.1558	0.1627	0.1698	0.1770	0.1843
15	0.0838	0.0899	0.0963	0.1030	0.1098	0.1168	0.1241	0.1315	0.1391	0.1468	0.1547
20	0.0672	0.0736	0.0802	0.0872	0.0944	0.1019	0.1095	0.1175	0.1256	0.1339	0.1424
25	0.0574	0.0640	0.0710	0.0782	0.0858	0.0937	0.1018	0.1102	0.1187	0.1275	0.1364
30	0.0510	0.0578	0.0651	0.0726	0.0806	0.0888	0.0973	0.1061	0.1150	0.1241	0.1334

Energy Economics: Solar PV and Wind Generation

Example 6

- An efficient air conditioner that costs an extra $1000 and saves $200 per year is to be paid for with a 7% interest, 10-year loan. Find the annual monetary savings.
- The capital recovery factor will be

$$\mathrm{CRF}(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$\mathrm{CRF}(0.07, 10) = \frac{0.07(1+0.07)^{10}}{(1+0.07)^{10} - 1}$$

$$= 0.14238/\mathrm{yr}$$

The annual payments will be $A = \$1000 \times 0.14238/yr$

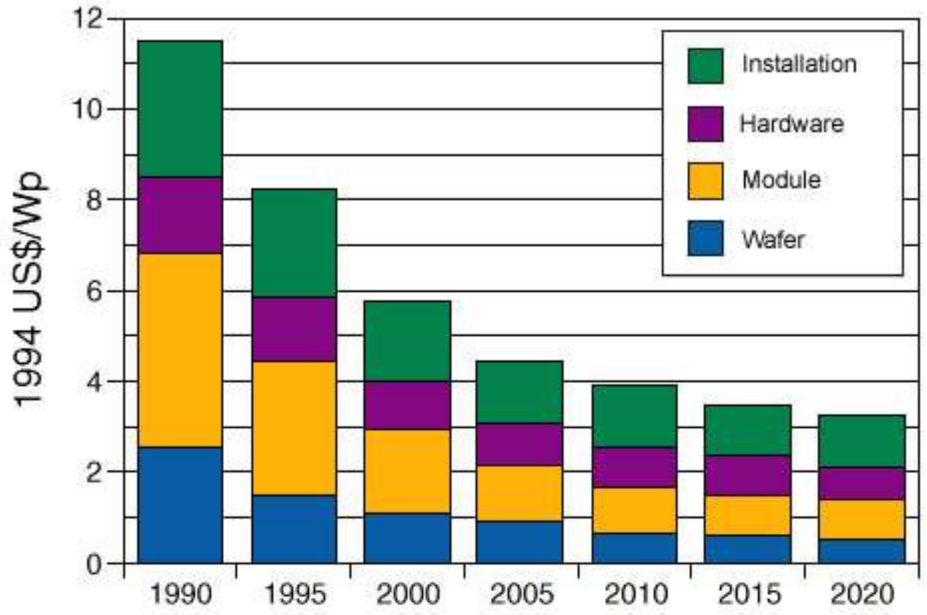
$$= \$142.38/\mathrm{yr}$$

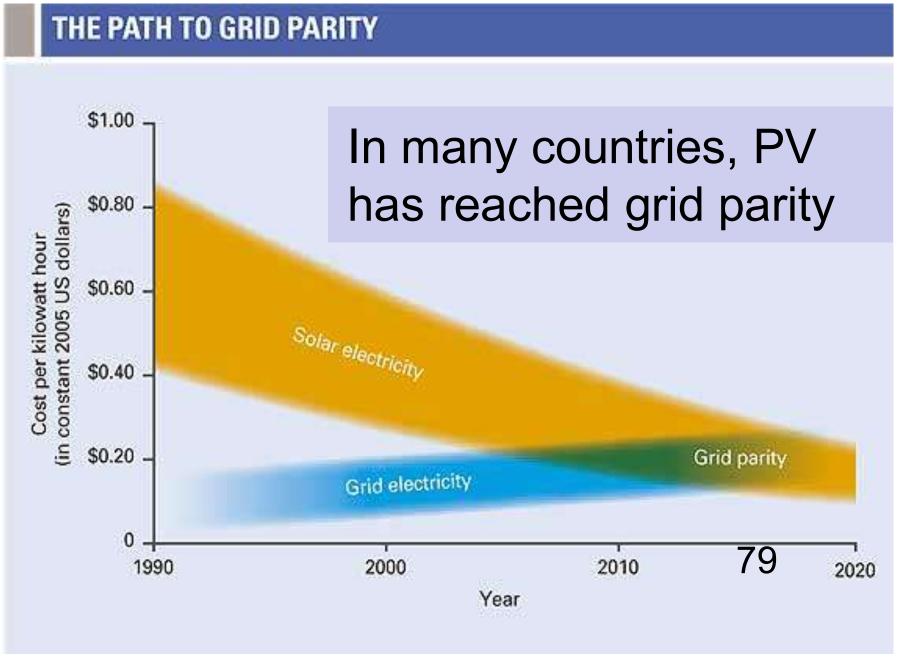
The annual savings will be $\$200 - \$142.38 = \$57.62/\mathrm{yr}$

$A_{final} = A_{savings} - A_{payment}$

Energy Economics: Solar PV

- The PV industry has seen dramatic drops in module prices in recent years
- Various incentives for electricity consumers to install and operate solar-electric generating systems
- Solar cell energy conversion efficiencies for commercially available photovoltaics are around 14–22%.
- In many locations, PV has reached grid parity, which is usually defined as PV production costs at or below retail electricity prices
- Payback time is calculated based on how much electricity is not brought from the grid





Example 7

- A 3-kW photovoltaic system, which operates with a capacity factor (CF) of 0.25, costs $10,000 to install. There are no annual costs associated with the system other than the payments on a 6%, 20-year loan. Find the cost of electricity generated by the system (¢/kWh)

– Find annual cost ($/year)

– Find annual energy (kWh/year)

Example 7

- A 3-kW photovoltaic system, which operates with a capacity factor (CF) of 0.25, costs $10,000 to install. There are no annual costs associated with the system other than the payments on a 6%, 20-year loan. Find the cost of electricity generated by the system (¢/kWh)

– Find annual cost ($/year) → Use CRF.

– Find annual energy (kWh/year) → Use CF.

Years	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%
5	0.2184	0.2246	0.2310	0.2374	0.2439	0.2505	0.2571	0.2638	0.2706	0.2774	0.2843
10	0.1172	0.1233	0.1295	0.1359	0.1424	0.1490	0.1558	0.1627	0.1698	0.1770	0.1843
15	0.0838	0.0899	0.0963	0.1030	0.1098	0.1168	0.1241	0.1315	0.1391	0.1468	0.1547
20	0.0672	0.0736	0.0802	0.0872	0.0944	0.1019	0.1095	0.1175	0.1256	0.1339	0.1424
25	0.0574	0.0640	0.0710	0.0782	0.0858	0.0937	0.1018	0.1102	0.1187	0.1275	0.1364
30	0.0510	0.0578	0.0651	0.0726	0.0806	0.0888	0.0973	0.1061	0.1150	0.1241	0.1334

- **The capital recovery factor = 0.0872/yr.**

The annual payments will be $CRF(0.06, 20) = \frac{0.06(1+0.06)^{20}}{(1+0.06)^{20}-1} = 0.0872/\text{year}$

$$A = P \times \text{CRF}(0.06, 20)$$
$$= \$10{,}000 \times 0.0872/\text{yr} = \$872/\text{yr}$$

To find the annual electricity generated, we use capacity factor (CF):

$$\text{Annual energy (kWh/yr)} = \text{Rated power (kW)} \times 8760 \text{ hr/yr} \times \text{CF}$$

$$\text{kWh/yr} = 3 \text{ kW} \times 8760 \text{ h/yr} \times 0.25 = 6570 \text{ kWh/yr}$$

The cost of electricity from the PV system is therefore

$$\text{Cost of PV electricity} = \frac{\$872/\text{yr}}{6570 \text{ kWh/yr}}$$

$$= \$0.133/\text{kWh} = 13.3¢/\text{kWh}$$

Renewable energy sources do not have fuel cost!! (which may increase over the years)

Levelized (Bus-Bar) Costs

- Levelized (Bus-bar) cost = ratio of $\boxed{\textit{equivalent}}$ annual cost to annual electricity energy.

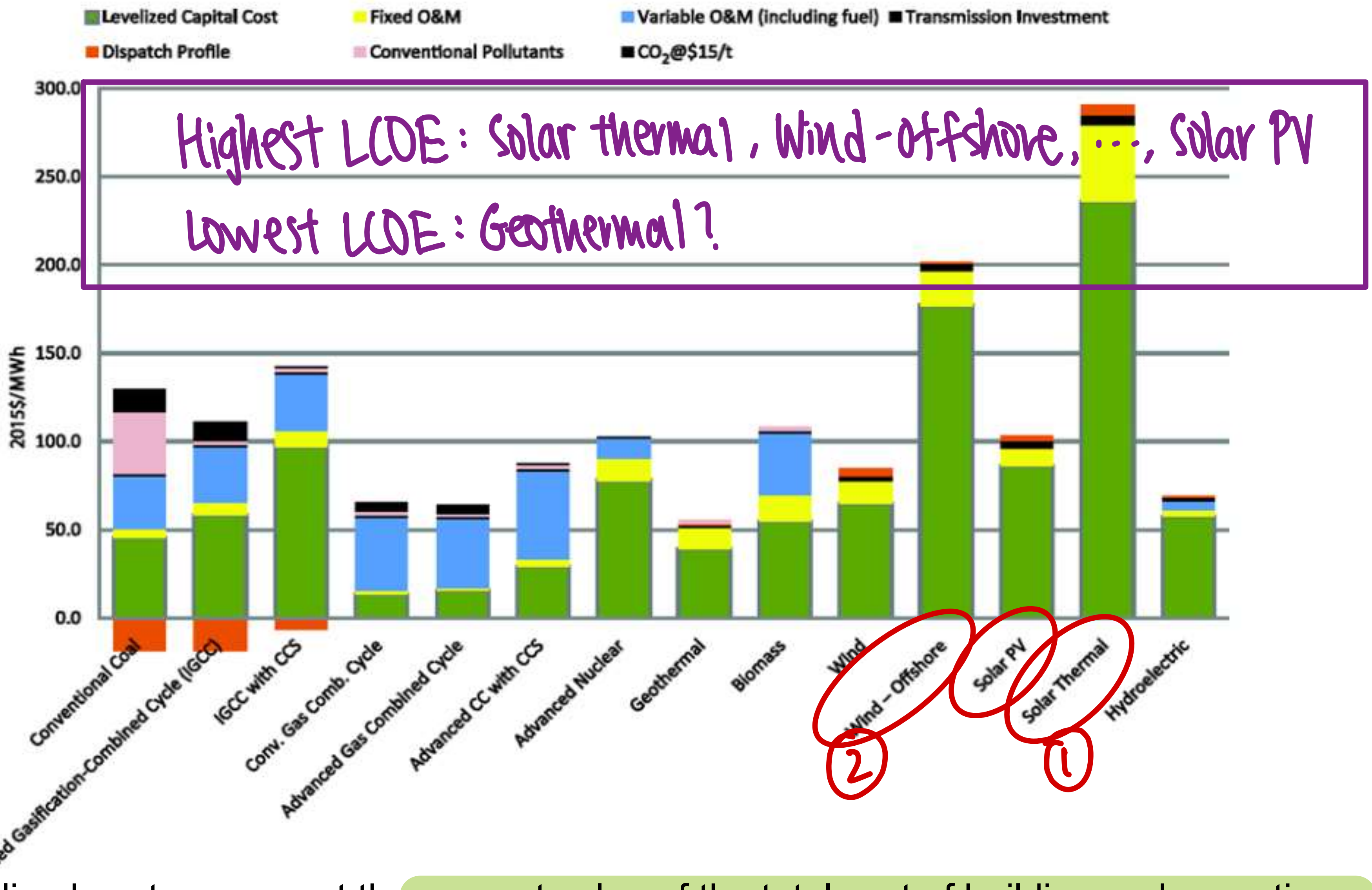
$$\text{Cost of electricity (\$/kWh)} = \frac{\text{Levelized annual cost (\$/yr)}}{\text{Annual energy (kWh/yr)}}$$

- Incorporates an increase in future fuel cost.

From US EIA Annual report, the annual cost comes from

"…their capital and operating costs, their availability and capacity factors, the financial structure and subsidies, the time to construct the plant, the utilization of the plant, ***and expected future cost changes, including fuel input for fossil and nuclear plants****."*

Levelized Cost of Electricity (LCOE)



Levelized costs represent the present value of the total cost of building and operating a generating plant over its financial life, converted to equal annual payments and amortized over expected annual generation from an assumed duty cycle

Estimated Levelized Cost of New Dispatchable Generation Resources, 2018

Plant type Dispatchable Technologies	U.S. average levelized costs (2011 $/megawatthour) for plants entering service in 2018 Capacity factor (%)	Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system levelized cost
Conventional Coal	85	65.7	4.1	29.2	1.2	100.1
Advanced Coal	85	84.4	6.8	30.7	1.2	123
Advanced Coal with CCS	85	88.4	8.8	37.2	1.2	135.5
Natural Gas-fired						
Conventional Combined Cycle	87	15.8	1.7	48.4	1.2	67.1
Advanced Combined Cycle	87	17.4	2	45	1.2	65.6
Advanced CC with CCS	87	34	4.1	54.1	1.2	93.4
Conventional Combustion Turbine	30	44.2	2.7	80	3.4	130.3
Advanced Combustion Turbine	30	30.4	2.6	68.2	3.4	104.6
Advanced Nuclear	90	83.4	11.6	12.3	1.1	108.4
Geothermal	92	76.2	12	0	1.4	89.6
Biomass	83	53.2	14.3	42.3	1.2	111

Estimated Levelized Cost of New Non-Dispatchable Generation Resources, 2018

Plant type Non-Dispatchable Technologies	U.S. average levelized costs (2011 $/megawatthour) for plants entering service in 2018 Capacity factor (%)	Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system levelized cost
Wind	34	70.3	13.1	0	3.2	86.6
Wind-Offshore	37	193.4	22.4	0	5.7	221.5
Solar PV[1]	25	130.4	9.9	0	4	144.3
Solar Thermal	20	214.2	41.4	0	5.9	261.5
Hydro[2]	52	78.1	4.1	6.1	2	90.3

IER

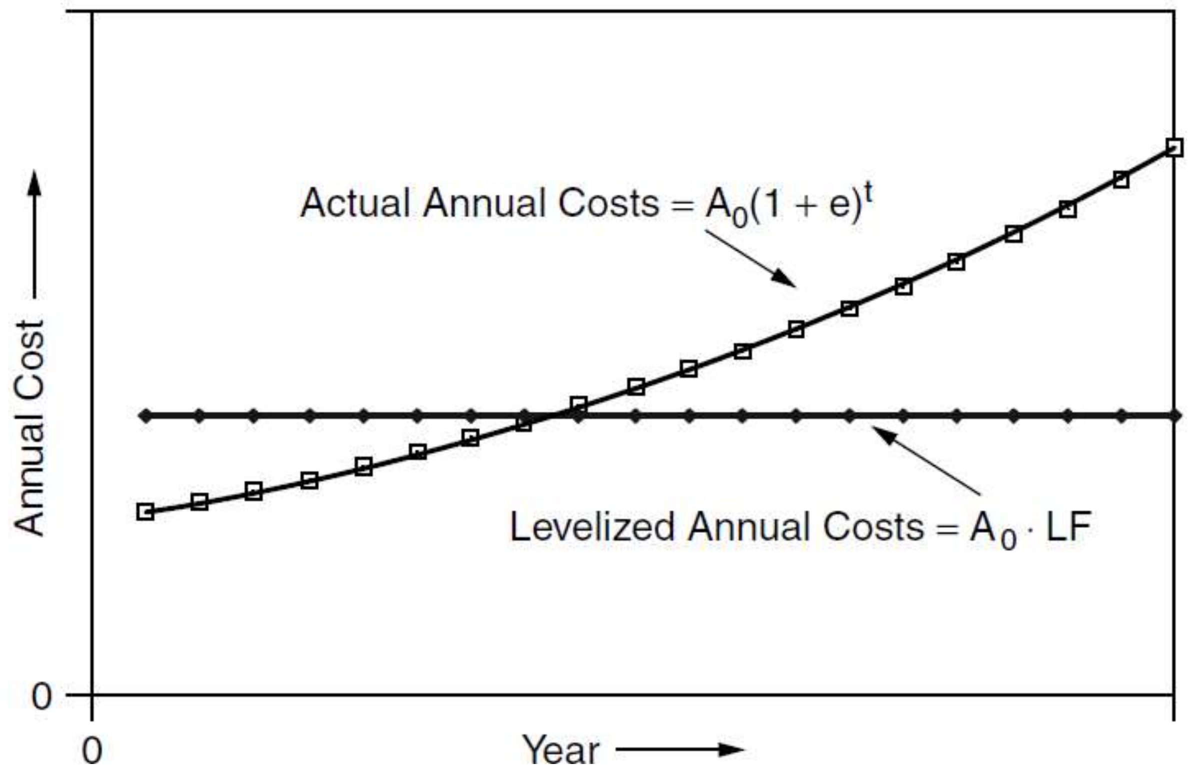
Source: Energy Information Administration, *Annual Energy Outlook 2013*

Present Value of Future Costs

- Assume an annual cost "A_0" today.
- Cost escalates due to inflation/ increasing fuel cost at the rate "e".
- Present value over a period of n years

Annual cost today

$$\mathrm{PV(annual\ costs)} = A_0 \cdot \mathrm{PVF}(d', n)$$



Annual cost today

$$d' = \frac{d - e}{1 + e}$$

Equivalent Annual Cost of Future Costs

annual cost today

- From present value of the increasing annual cost,

$$\text{PV(annual costs)} = A_0 \cdot \text{PVF}(d', n)$$

- The equivalent annual cost is found from capital recovery factor,

$= A_0 \cdot LF$

$$\text{Levelized annual costs} = A_0 \boxed{[\text{PVF}(d', n) \cdot \text{CRF}(d, n)]}$$

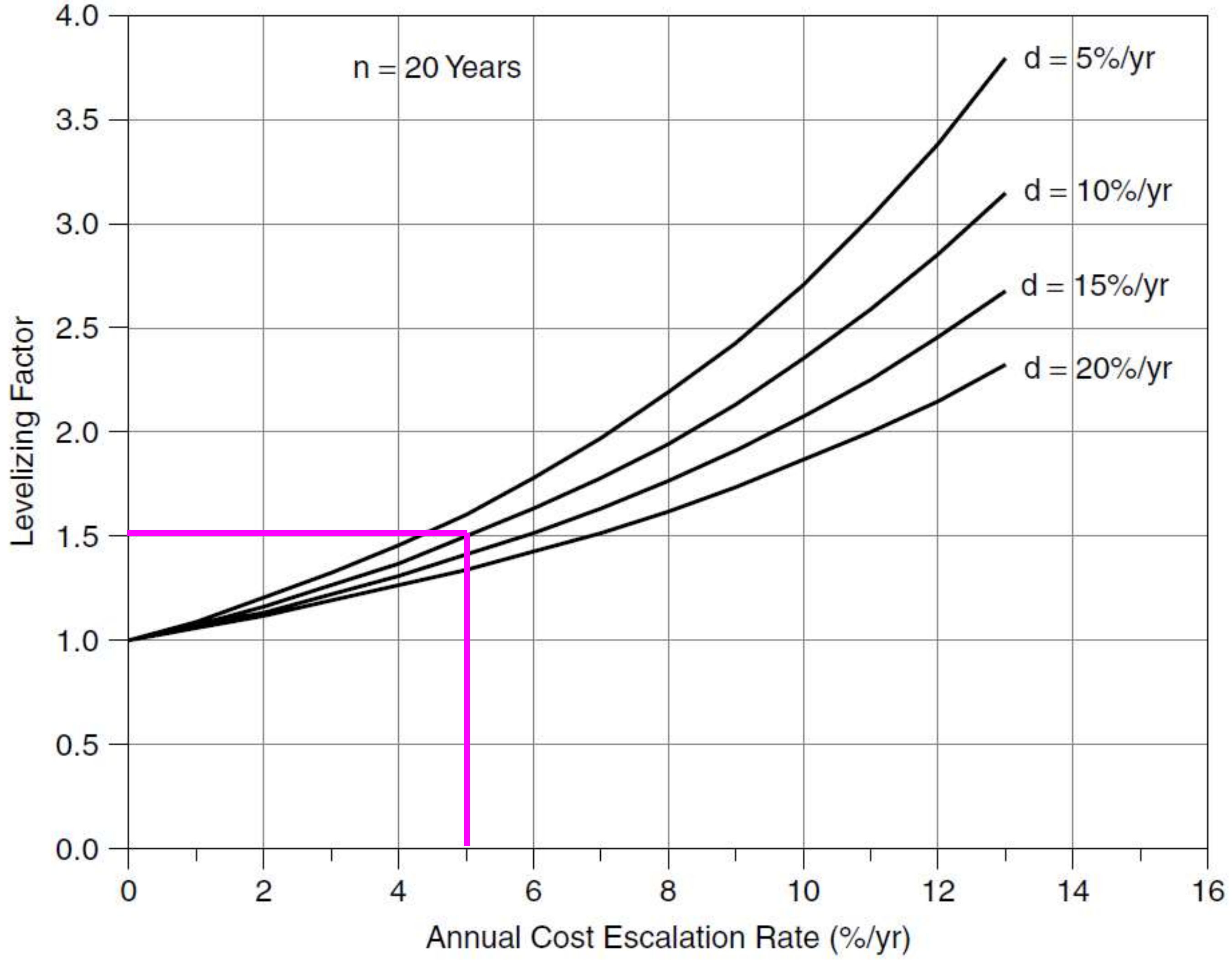
$$\boxed{\text{Levelizing factor (LF)} = \left[\frac{(1+d')^n - 1}{d'(1+d')^n}\right] \cdot \left[\frac{d(1+d)^n}{(1+d)^n - 1}\right]}$$

LF is a multiplier that converts the escalating annual fuel and O&M costs into a series of equal annual amounts

operational & maintenance

When there is no escalation, e = 0, then d' = d
And LF = 1

Impact of Levelizing Factor (LF)



LF can be significant, depending on the discount rate and cost escalation rate.

Fixed Charge Rate (FCR)

- Levelizing factor (LF) is used to levelize the **variable cost** of a power plant.
- Fixed charge rate (FCR) is used to levelize the **capital cost** of a power plant.
- FCR incorporates the following costs.
  - Depreciation
  - Return of investment
  - Insurance
  - Tax
- 10-18% per year.

Levelized Total Costs

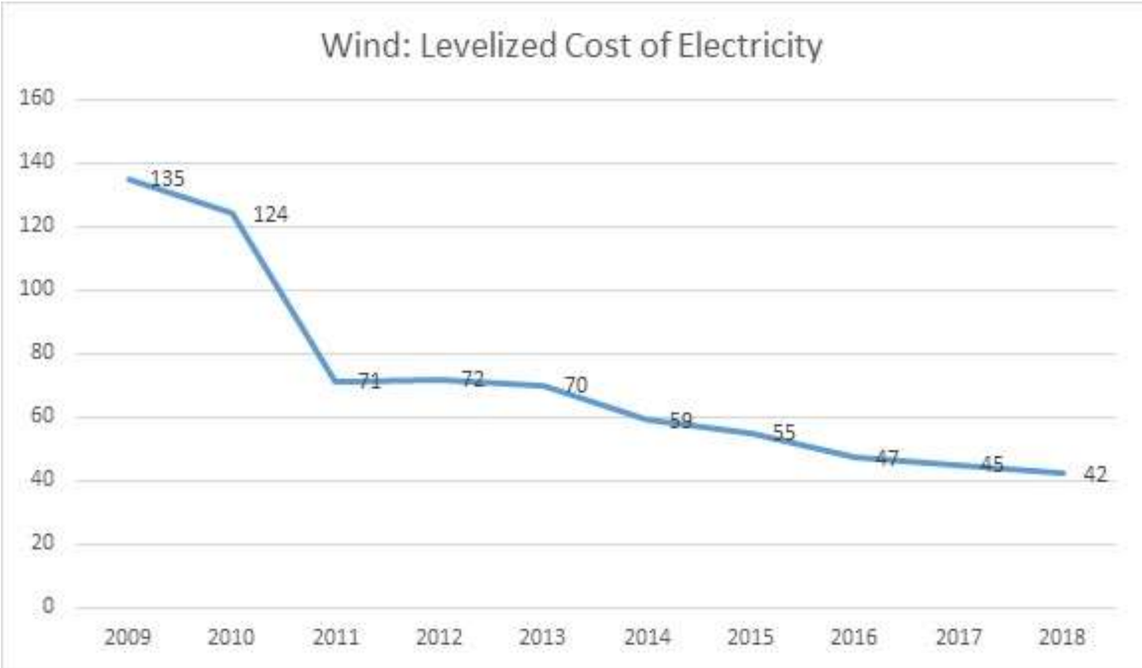
- Levelized cost is a convenient summary measure of the overall competitiveness of different generating technologies.
- For technologies such as solar and wind generation that have no fuel costs and relatively small variable O&M costs, it changes in rough proportion to the estimated capital cost of generation capacity

- Levelized annual cost,

$$\text{Levelized fixed cost}(\$/\text{kWh}) = \frac{\text{Capital cost}(\$/\text{kW}) \times \text{FCR}(1/\text{yr})}{8760\ \text{h/yr} \times \text{CF}}$$

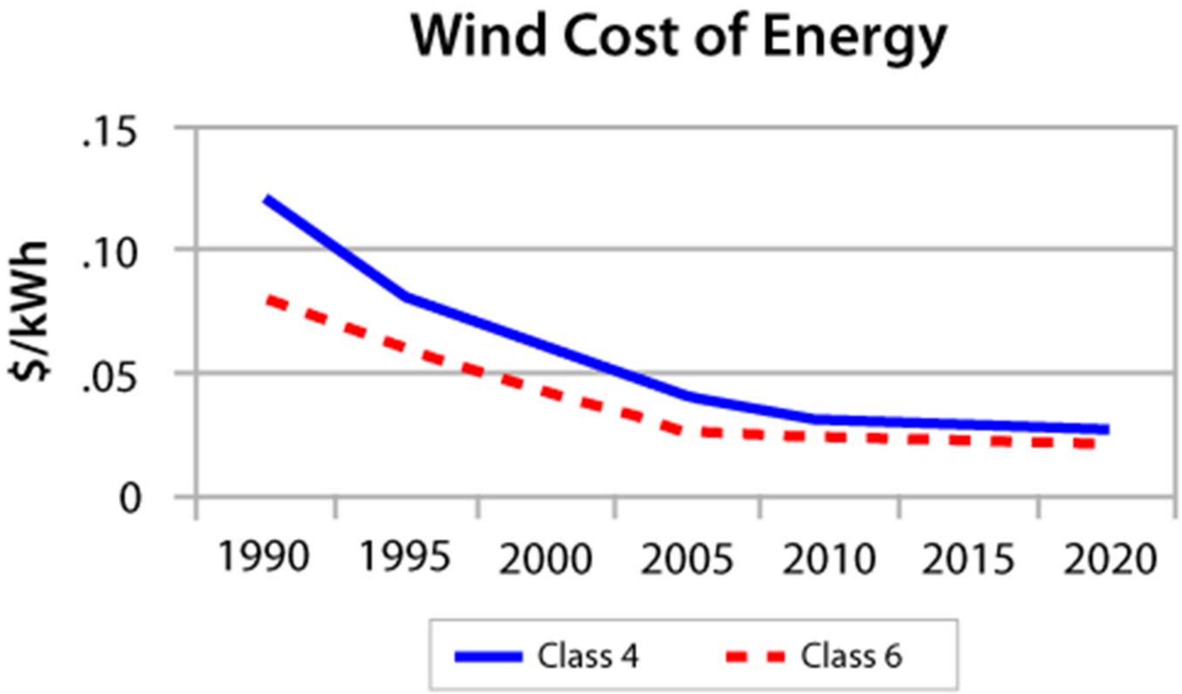
Wind Turbine Economics

- **Wind power is capital intensive, but has no fuel costs.**
- The price of wind power is much more stable than the volatile prices of fossil fuel sources.
- Expected to become the cheapest form of energy generation in the future.
- Falling prices continue to drive the levelized cost down



Wind Turbine Economics

- Wind energy systems reached general grid parity in Europe in 2010, and reached grid parity in the US in 2016.
- For offshore wind projects, the economics depend on the distance from shore because turbine foundation costs increase rapidly with increasing water depth. Offshore wind turbines are generally much larger than land-based turbines.



Example 8: Wind Turbine Economics

A 900-W Whisper H900 wind turbine, 7-ft diameter (2.13 m) blade costs \$1600. By the time the system is installed and operational, it costs a total of \$2500, which is to be paid for with a 15-yr, 7 percent loan. Assuming O&M costs of \$100/yr, estimate the cost per kWhr over the 15-year period if average windspeed at hub height is 15 mph (6.7 m/s).

Find the annualized cost from CRF function, with interest rate of 7% for 15 years.

The capital recovery factor for a 7%, 15-yr loan would be

$$\text{CRF}(0.07, 15\text{ yr}) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$= \frac{0.07(1+0.07)^{15}}{(1+0.07)^{15} - 1} = 0.1098/\text{yr}$$

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Find the annualized cost from CRF function, with interest rate of 7% for 15 years.

The annual payments on the loan would be:

$$A = P \times \text{CRF}(0.07, 15)$$

$$= \$2500 \times 0.1098/\text{yr} = \$274.49/\text{yr}$$

The annual cost, including $100/yr of O&M cost

= $274.49 + 100

= $374.49/yr

- Using the capacity factor approach to estimate the energy delivered by this machine in 6.7 m/s wind:

$$\mathrm{CF} = 0.087\overline{V}\,(\mathrm{m/s}) - \frac{P_R(\mathrm{kW})}{D^2(m^2)}$$

$$= 0.087 \times 6.7 - \frac{0.90}{2.13^2} = 0.385$$

- The annual energy delivered:

$$\mathrm{kWh/yr} = 0.90\ \mathrm{kW} \times 8760\ \mathrm{h/yr} \times 0.385 = 3035\ \mathrm{kWh/yr}$$

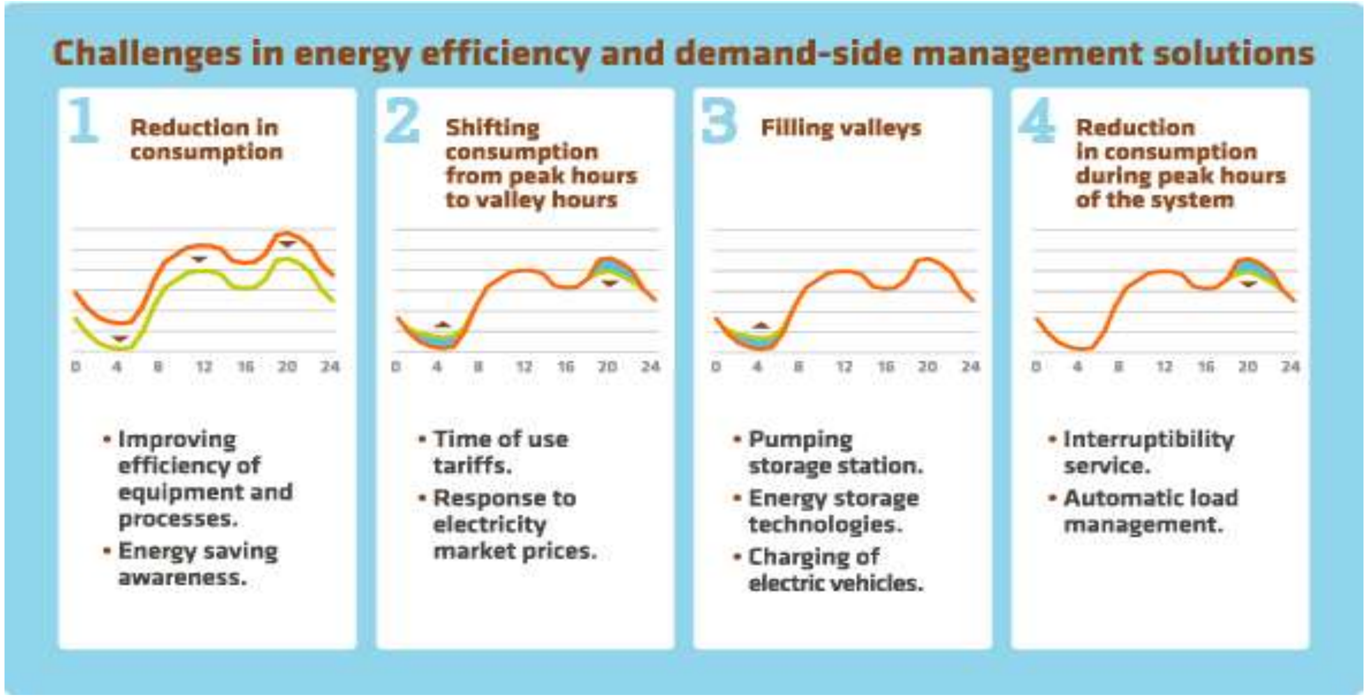
$$\text{Average cost} = \frac{\text{Annual cost (\$/yr)}}{\text{Annual energy (kWh/yr)}}$$

$$= \frac{\$374.49/\text{yr}}{3035\ \text{kWh/yr}} = \$0.123/\text{kWh}$$

Demand Side Management (DSM)

Types of DSM Measures

- **Conservation programmes**
- **Energy efficiency programmes** - reducing demand through more efficient processes, buildings or equipment
- **Load management programmes** - changing the load pattern and encouraging less demand at peak times and peak rates



Cost of Conserved Energy

Cost of Conserved Energy

- CCE is used to compare the value of saved energy among different energy saving options.

Can be found through 'Capital Recovery Factor' CRF

Extra cost required for an energy saving project

$$\text{CCE} = \frac{\boxed{\text{Annualized } \boxed{\text{cost of conservation}} \text{ (\$/yr)}}}{\text{Annual energy saved (kWh/yr)}}$$

If cost of conservation measure is only the initial capital:

- use CRF

If there are additional annual costs, then:

- Perform levelized cost analysis
- Obtain present value of all future costs
- Annualize them using CRF

How much are we paying to save 1 kWh energy!?!?

Example 9: Energy conservation

New lamps cost about \$50 in parts and labour. More efficient ballasts cost \$65 but will decrease the power needed by the fixture from 170 W to 120 W.

Assume that electricity from the utility costs 8¢/kWh.

For an office in which the lamps are on 3000 h/yr, what is the cost of conserved energy for the better system if it is financed with a 15-yr, 8% loan, assuming that the new components last at least that long (15 years)?

Extra cost for better energy saving alternative is 65-50 = 15, annualized cost is found from CRF.

From the table,

CRF(0.08, 15) = 0.1168/yr

Years	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%
5	0.2184	0.2246	0.2310	0.2374	0.2439	0.2505	0.2571	0.2638	0.2706	0.2774	0.2843
10	0.1172	0.1233	0.1295	0.1359	0.1424	0.1490	0.1558	0.1627	0.1698	0.1770	0.1843
15	0.0838	0.0899	0.0963	0.1030	0.1098	0.1168	0.1241	0.1315	0.1391	0.1468	0.1547
20	0.0672	0.0736	0.0802	0.0872	0.0944	0.1019	0.1095	0.1175	0.1256	0.1339	0.1424
25	0.0574	0.0640	0.0710	0.0782	0.0858	0.0937	0.1018	0.1102	0.1187	0.1275	0.1364
30	0.0510	0.0578	0.0651	0.0726	0.0806	0.0888	0.0973	0.1061	0.1150	0.1241	0.1334

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Assume that electricity from the utility costs 8¢/kWh.

For an office in which the lamps are on 3000 h/yr, what is the cost of conserved energy for the better system if it is financed with a 15-yr, 8% loan, assuming that the new components last at least that long (15 years)?

The annualized cost of the improvement is

$$A = P \times CRF(i, n)$$

$$= \$15 \times 0.1168/\text{yr} = \$1.75/\text{yr}$$

$$\text{Saved energy} = (170 - 120)\text{W} \times 3000\ \text{h/yr} \div (1000\ \text{W/kW})$$

$$= 150\ \text{kWh/yr}$$

- The cost of conserved energy is

$$\text{CCE} = \frac{\$1.75/\text{yr}}{150\ \text{kWh/yr}}$$

$$= \$0.0117/\text{kWh} = 1.17¢/\text{kWh}$$

The choice is therefore to spend 8¢ to purchase 1 kWh for illumination

or

Spend 1.17¢ to avoid the need for that kWh.

There are added benefits from reduction in demand charges with the more efficient system.

What if the company has different energy saving projects, which project should be implemented and based on what ground?

Energy Conservation Supply Curve

- Indicates marginal cost of conserved energy versus cumulative energy saved.
  - Rank projects from the cheapest to the most expensive.
  - Draw a curve between CCE and cumulative energy saved (similar to 'supply' curve).

- Useful for policy makers to estimate total energy reduction with cost that is less than electricity cost.

By analyzing a number of efficiency measures and then graphing their potential cumulative savings, policy makers can estimate the total energy reduction that might be achievable at a cost less than that of purchased electricity.

Energy Conservation Supply Curve

Example 10: Consider four hypothetical conservation measures A, B, C, and D. The individual costs of conserved energy and individual annual energy savings values for these measures are shown in the table below.

Conservation Measure	CCE (¢/kWh)	Saved Energy (kWh/yr)
A	1	300
B	2	200
C	3	500
D	10	200

(1) Compute the cost of conserved energy (CCE) for each measure

(2) Plot an appropriate energy conservation supply curve.

(3) what is the average CCE if all four measures are implemented at the same time?

Example 10

Conservation Measure	CCE (¢/kWh)	Saved Energy (kWh/yr)	Cumulative Energy Saved (kWh/yr)	Cumulative Cost (¢/yr)
A	1	300	300	300
B	2	200	500	700
C	3	500	1000	2200
D	10	200	1200	4200

This is when the marginal cost of energy saving project is above price of electricity.

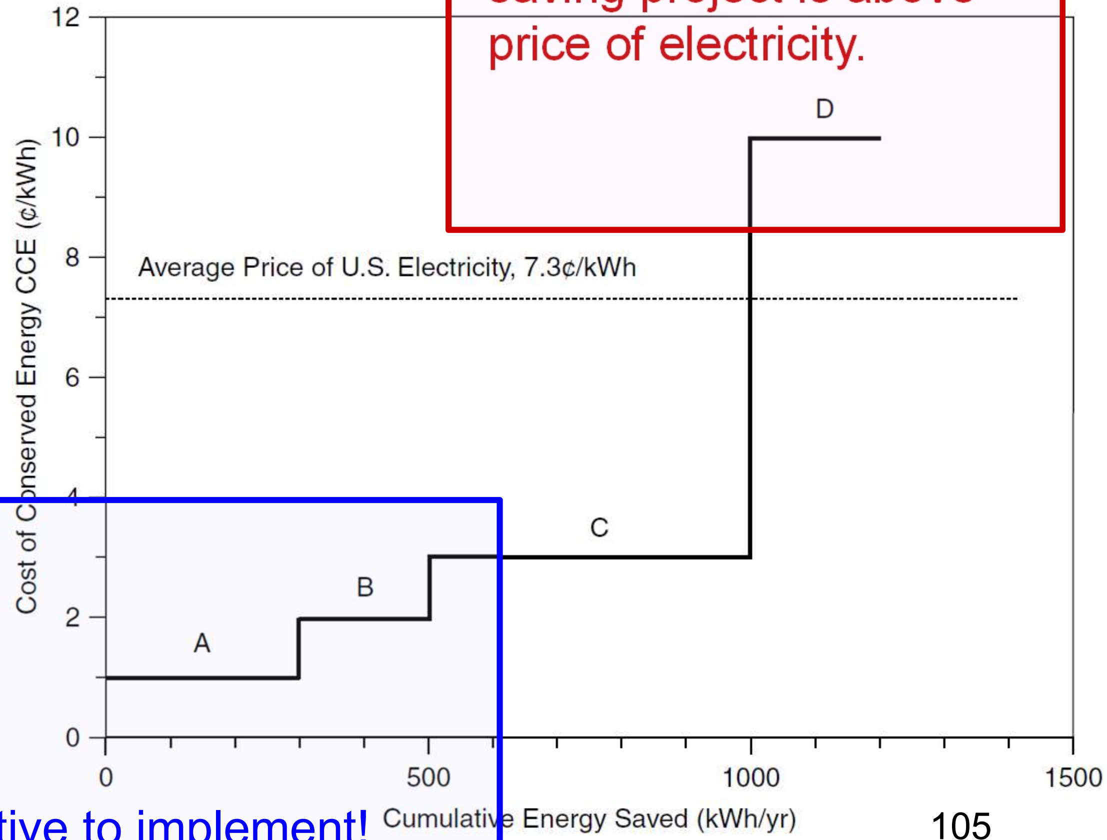
Total energy saving = 1200 kWh/yr

Total cost = 4200 ¢/year

Average CCE = 4200/1200

For all four measures, the average CCE is 2.85 ¢/kW-h.

Should we implement all four measures when the average price of electricity is 7.3 ¢/kW-h?



It is cost effective to implement!
Saving total of 1000 kWh/yr

Energy Efficiency/Reduction Programs

- Improving performance of boilers, steam systems, etc.
- Efficient Lighting
  - CFLs
  - Using natural light
- Appliance Labelling
- Building regulations
  - Efficient and alternative energy use
- Efficient use of electric motors
- Preventative maintenance
- Energy management

How to Enhance Energy Efficiency?

On generation side

- Improved technologies
- Relook at energy conversion process
  - Possible to use waste heat to supply some other processes?
  - Enhance cogeneration of both electricity and heat.

On demand side

- Recognize a true need of energy service
- For Illumination
  - Better lamps and fixture
- For industry
  - More efficient motors and controls

Need integrated resources planning considering both generation and demand.

Combined Heat And Power : Motivation

- Waste heat from electricity generation process should be utilized.
  - Process steam
  - Absorption cooling
  - Space heating

- Some considerations:
  - Distance from source
  - Magnitude of the temperature for different applications

Energy Efficiency Measure

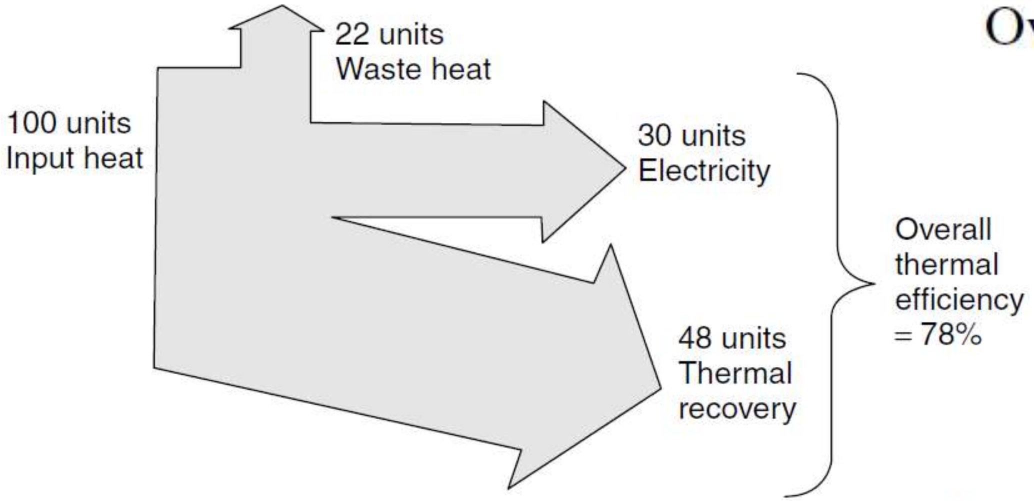
- Simple measure to combine the efficiency of both electrical and thermal energy.

$$\text{Overall thermal efficiency} = \left(\frac{\text{Electrical} + \text{Thermal ouput}}{\text{Thermal input}}\right) \times 100\%$$

- Consider two systems
  - 75% efficient boiler generates no electricity.
  - Cogeneration deliver 35% electrical output and 40% thermal output.

What is the difference between the efficiencies of the two systems?

Overall Efficiency Comparison

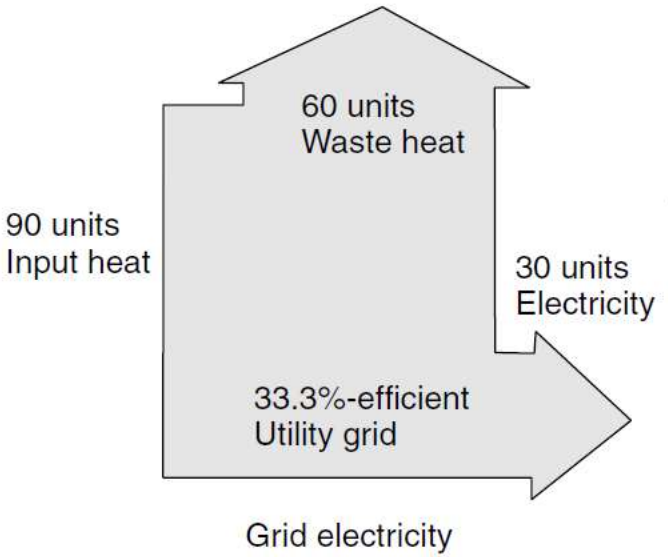


Overall thermal efficiency (with CHP)

$$\left(\frac{30+48}{100}\right) \times 100\% = 78\%$$

Overall thermal efficiency (without CHP)

$$\left(\frac{30+48}{90+60}\right) \times 100\% = 52\%$$



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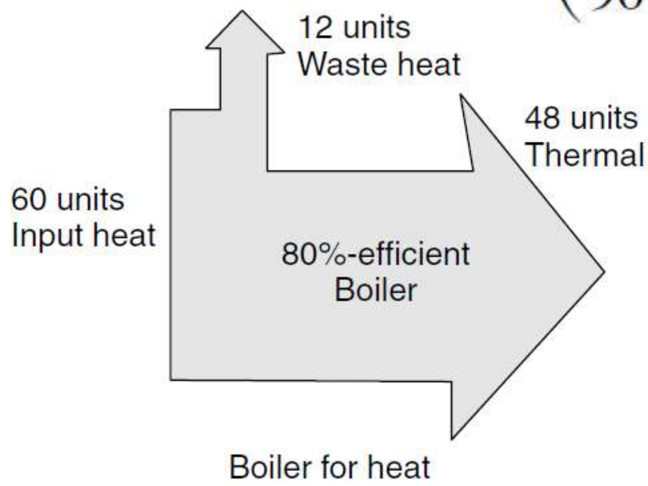


Overall Energy Saving with CHP

- Combined Heat & Power results in overall efficiency improvement from fuel savings.
- *percentage difference* between **thermal inputs** with and without CHP.

$$\text{Overall energy savings} = \left(1 - \frac{\text{Thermal input with CHP}}{\text{Thermal input without CHP}}\right) \times 100\%$$

- In the previous example, overall energy saving is,

$$\text{Overall energy savings} = \left(1 - \frac{100}{90 + 60}\right) \times 100\%$$

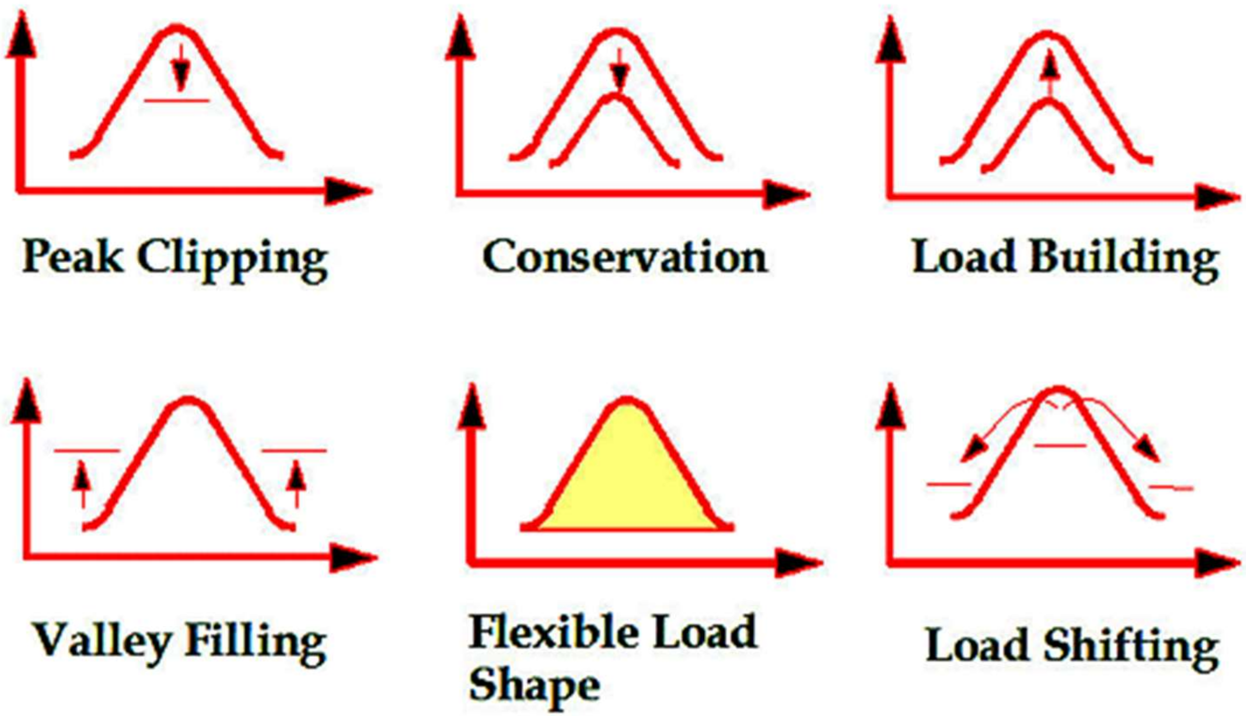
$$= 33.3\%$$

Load Management Measures

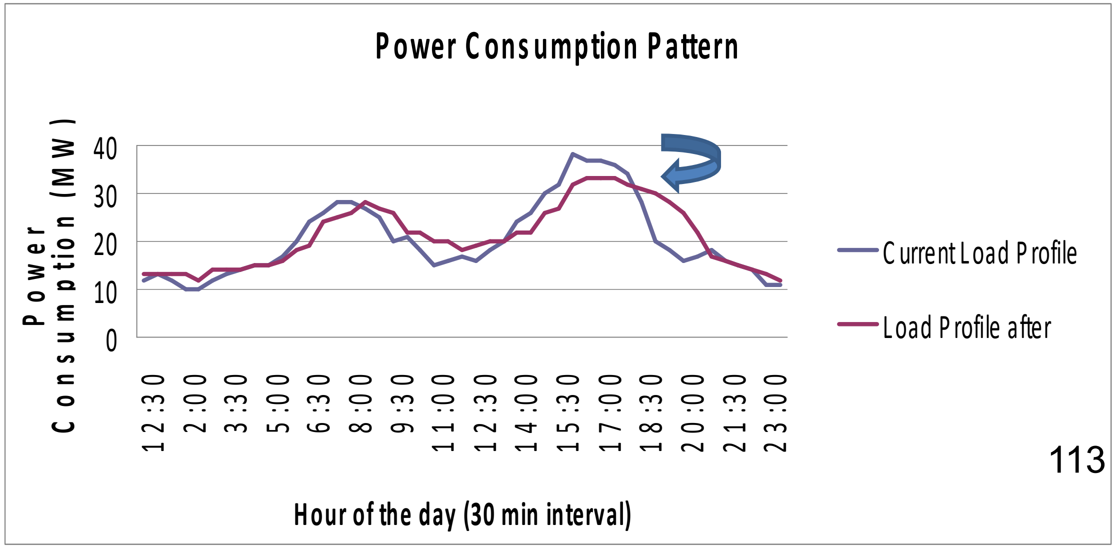
- Load Levelling:
  - Peak clipping
  - Valley filling
  - Load shifting
- Load Control:
  - Loads (e.g. heating, cooling, ventilation, and lighting) switched on or off, often remotely, by the utility
- Tariff Incentives or Penalties:
  - Time-of-Use & real time pricing
  - power factor penalties

Demand Side Management – Load Management

Several strategies to alter the shape of the load demand curve:



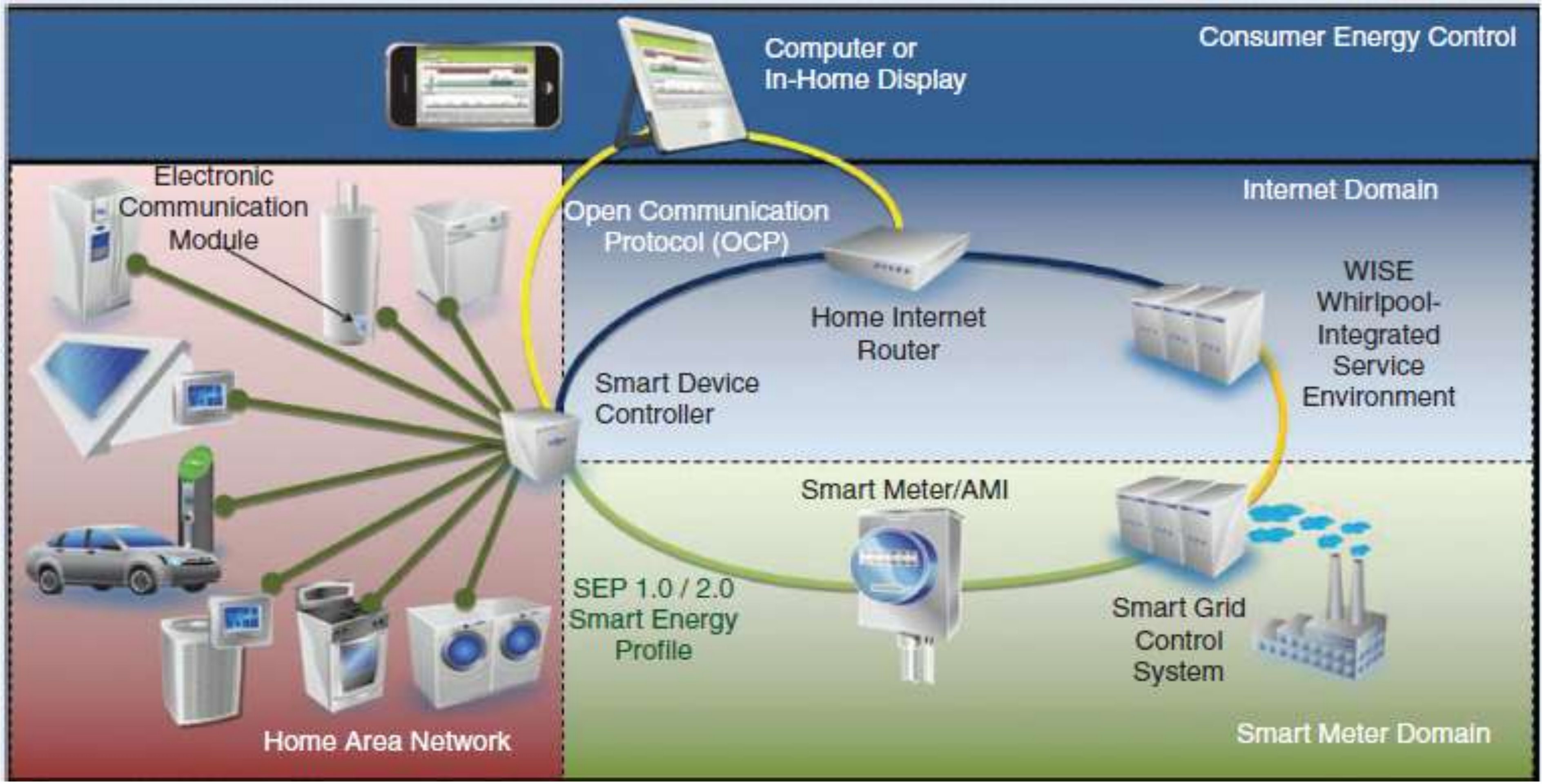
DSM strategies reduce/shift the load at peak hours to off-peak hours:



Benefits of Demand Side Management

Customer Benefits	Utility Benefits	Societal Benefits
Satisfy electricity demands	Lower cost of service	Reduce environmental degradation
Reduce / stabilize costs or electricity bill	Improve operating efficiency, Flexibility	Conserve resources
Maintain/improve lifestyle and productivity	Improve customer service	Protect global environment

Example: Demand side management using Smart Device Network (Whirlpool)

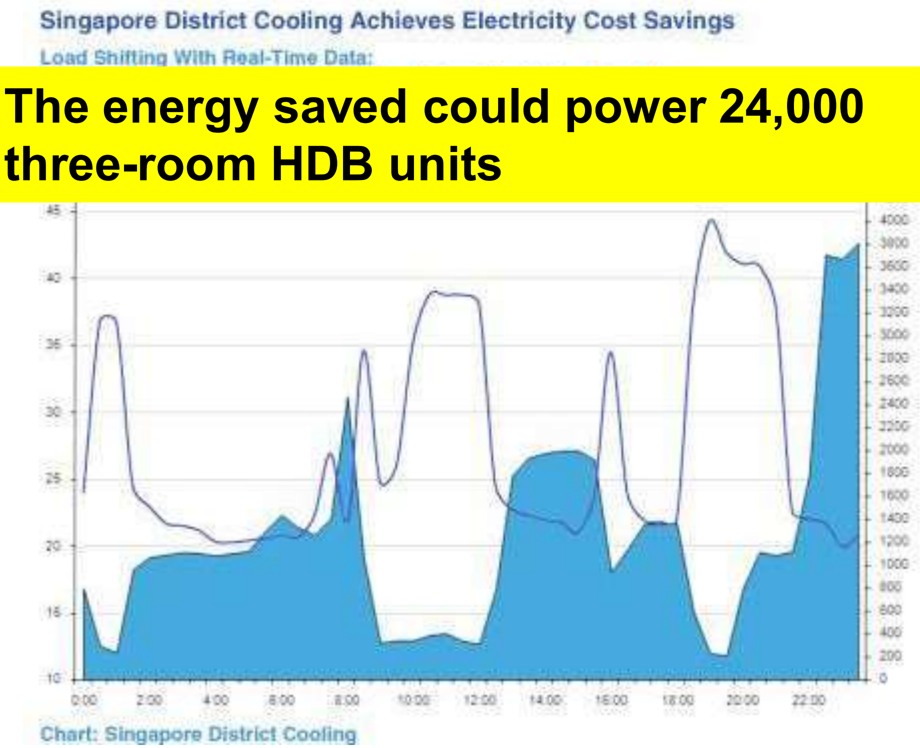


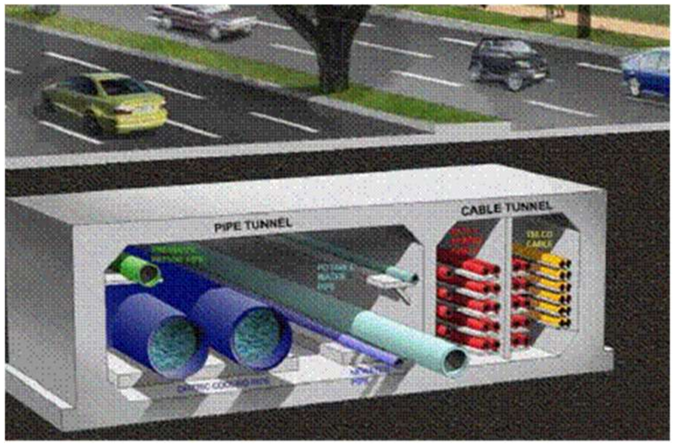
- **Smart Device Controller (SDC)** will monitor, control and coordinate activities of appliances and other smart devices; also acts as the central gateway

Singapore District Cooling

- An example of demand side management in Singapore.
- Use electricity to charge thermal energy storage system.
- Shift the charging period during low price and discharge during high price. https://www.youtube.com/watch?v=XM08h6xI9Rw
- World's largest cooling plant by capacity!
- District cooling is an energy-efficient and cost-effective method to provide buildings in the area with an optimal indoor climate.

The energy saved could power 24,000 three-room HDB units





Summary – Energy Economics

- **Utility rate structure**
  – Different utility rate structures are designed to provide incentives to end users to reduce electricity.

- **Energy economics**
  – **Net Present Value ($)** is used to compare two investment options.
  – **Internal Rate of Return (%)** is a measure to compare different investment options.
  – **Present value function (PVF) (year)** is used to convert the annualized budget to the total budget.
  – **Capital recovery factor (CRF) (/year)** is used to convert the total loan to annualized payment.

Summary – Energy Efficiency and DSM

- Energy conservation supply curves
  - Simple measure to analyze economic benefits of distributed resources/energy efficiency projects.
  - The supply curves provides a cost per kW-h and amount of electricity to be reduced for each measure.

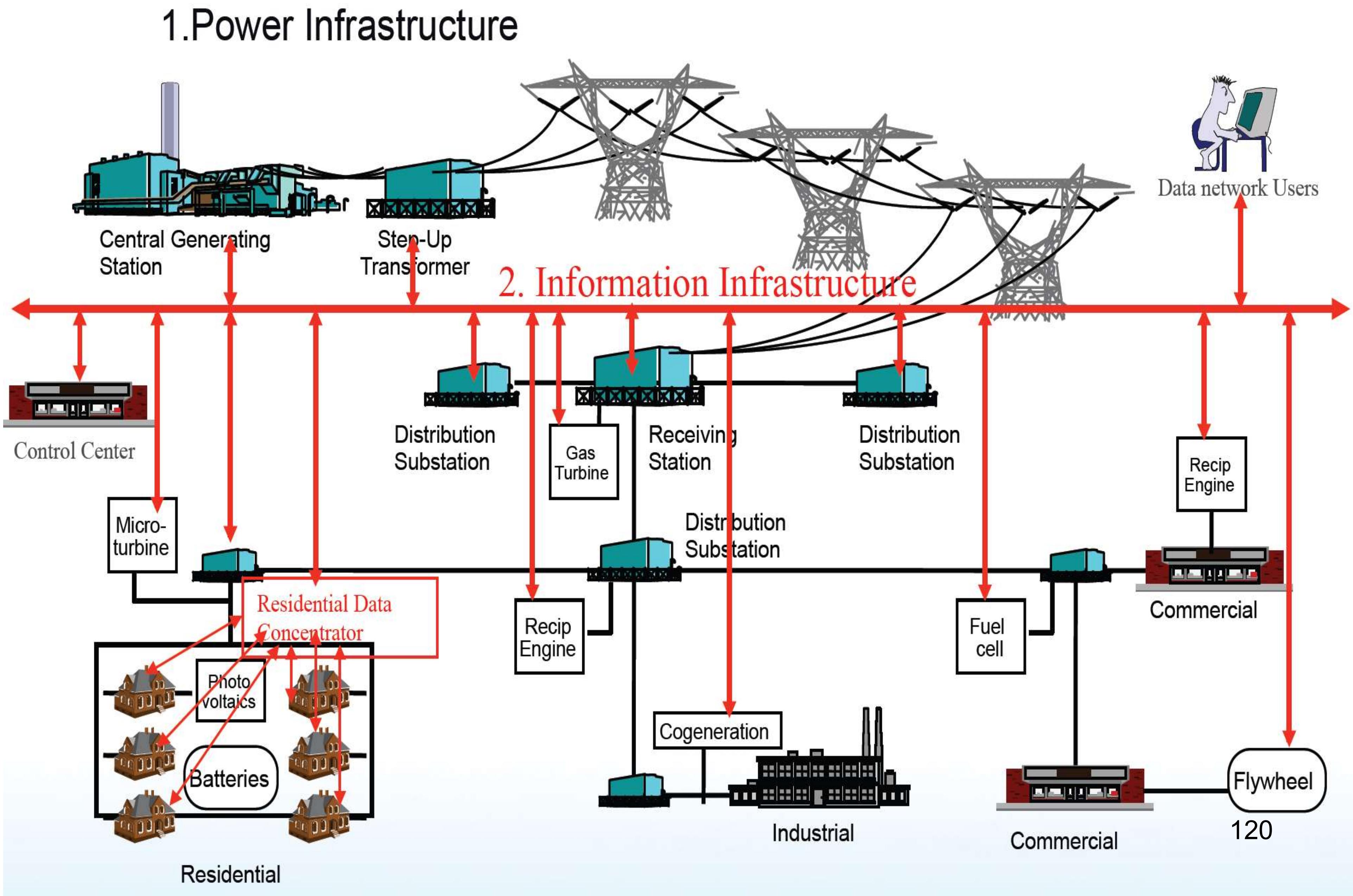
- Combined heat and power (CHP)

  Economic benefit of CHP to electricity output can be quantified using the following measure:
  - Energy chargeable to power (ECP)

- **Integrated resource planning and demand side management**
  - Various cost-effectiveness measures.

Smart Grid and Microgrid

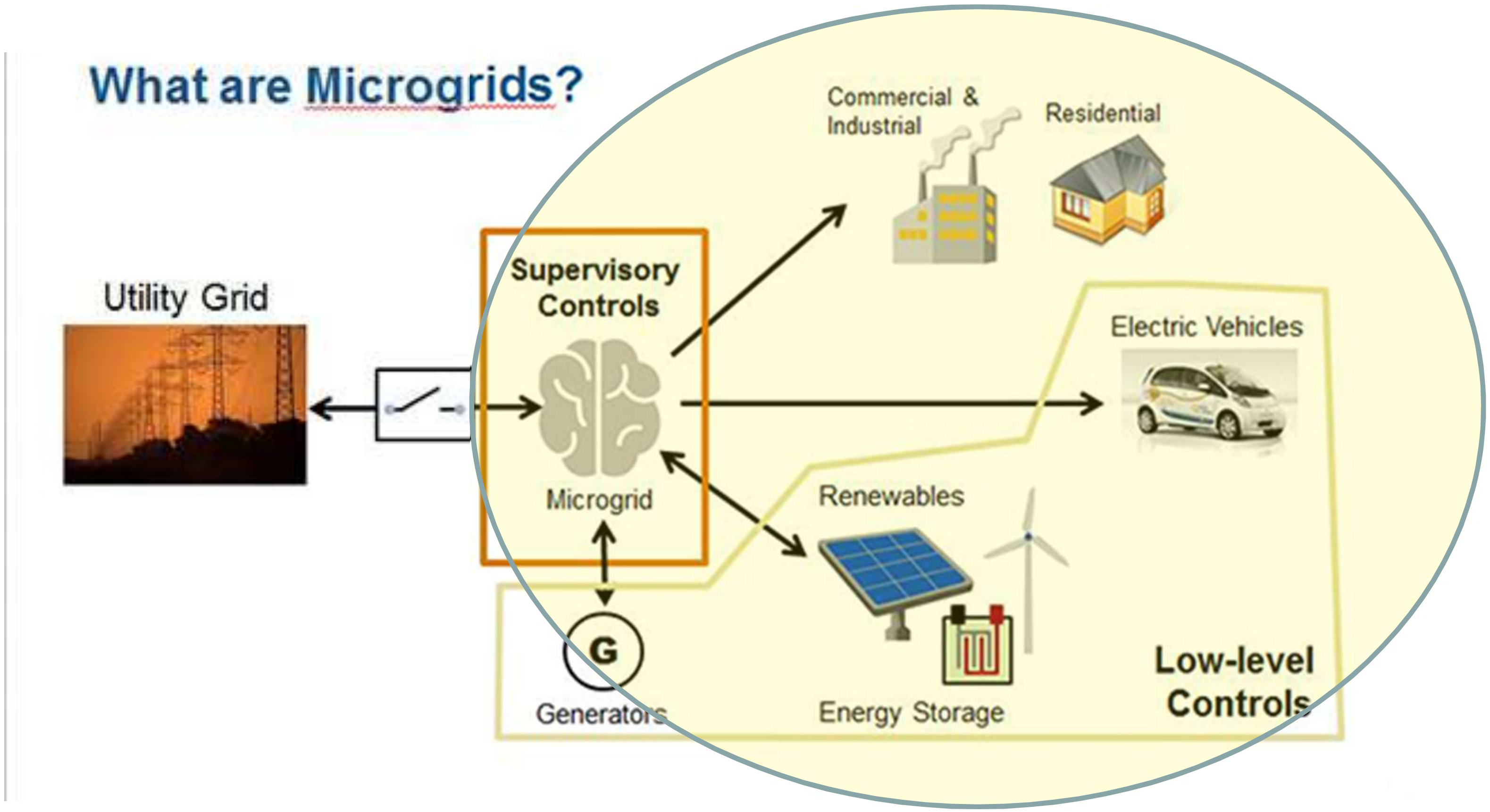
The Smart Grid will be Realized at the Microgrid Level and then Aggregated



Microgrid

A microgrid is an islandable part of a power delivery system that:

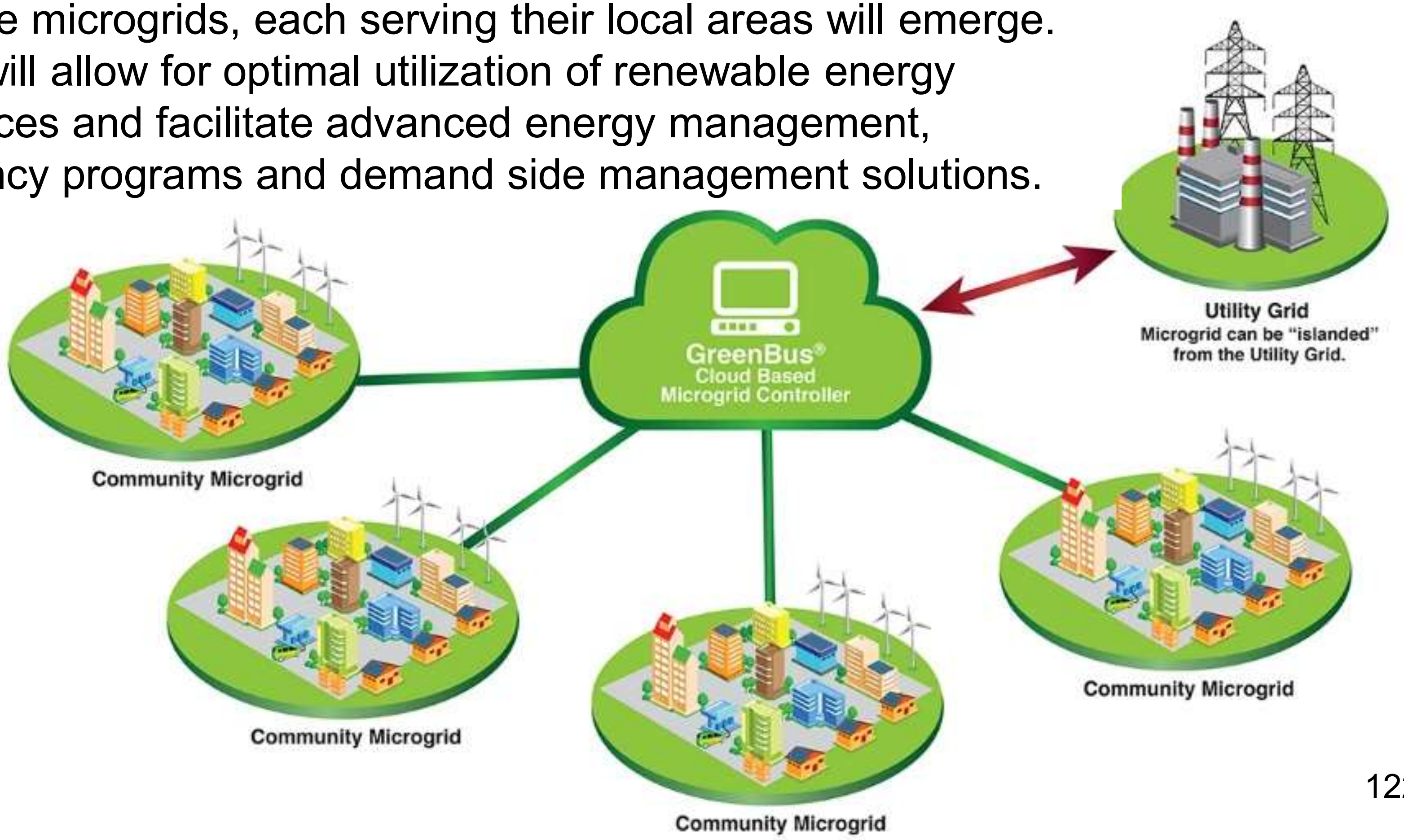
- Serves one or more consumers
- Incorporates DERs and/or is connected to the utility grid
- May range in size from a city block to a small city



Microgrid

Future electricity infrastructure will be highly decentralized, with many microgrids catering to clusters of end-user loads, as opposed to one centralized generating station serving as the supply center

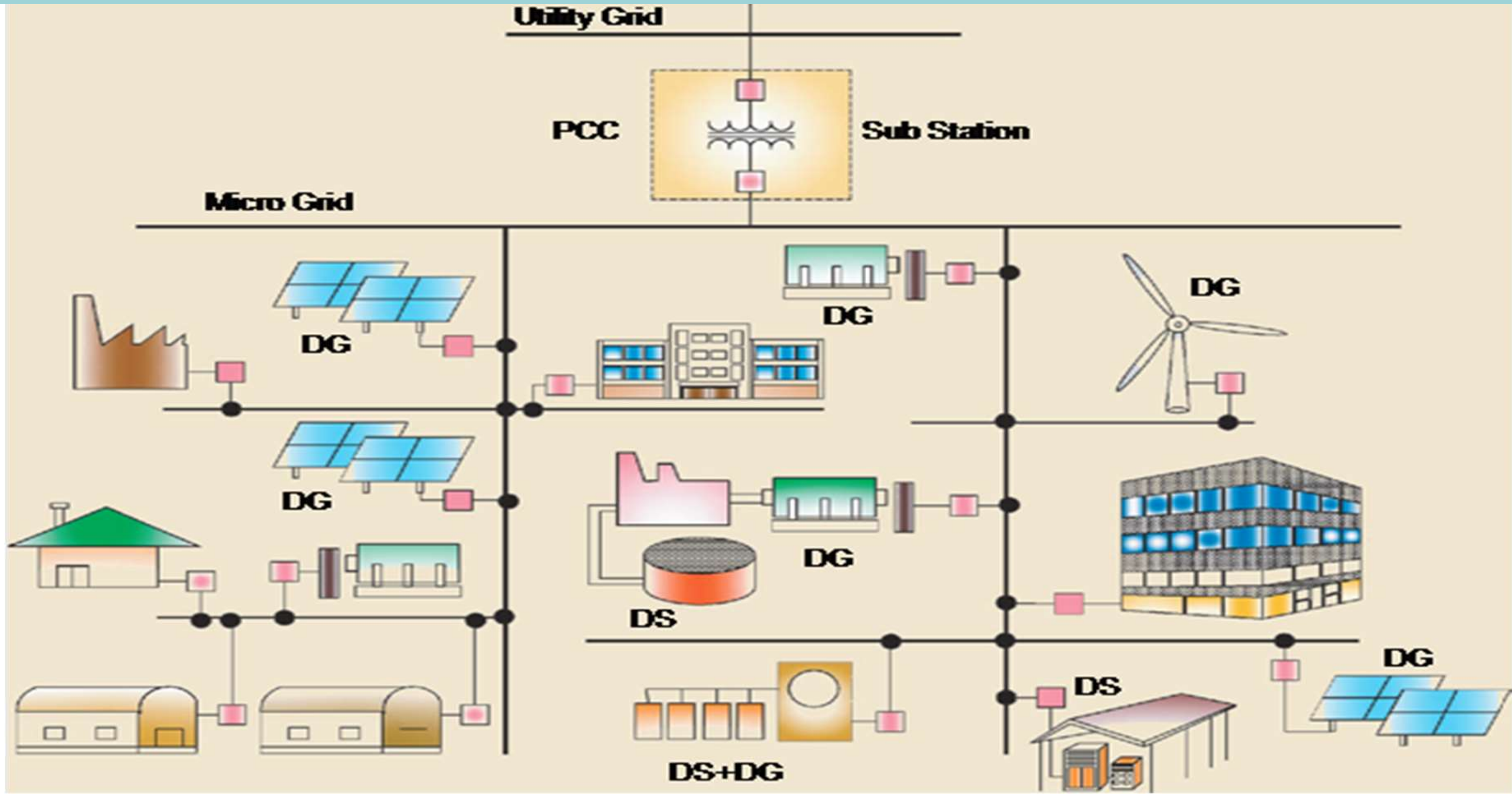
- Multiple microgrids, each serving their local areas will emerge.
- They will allow for optimal utilization of renewable energy resources and facilitate advanced energy management, efficiency programs and demand side management solutions.



Microgrid

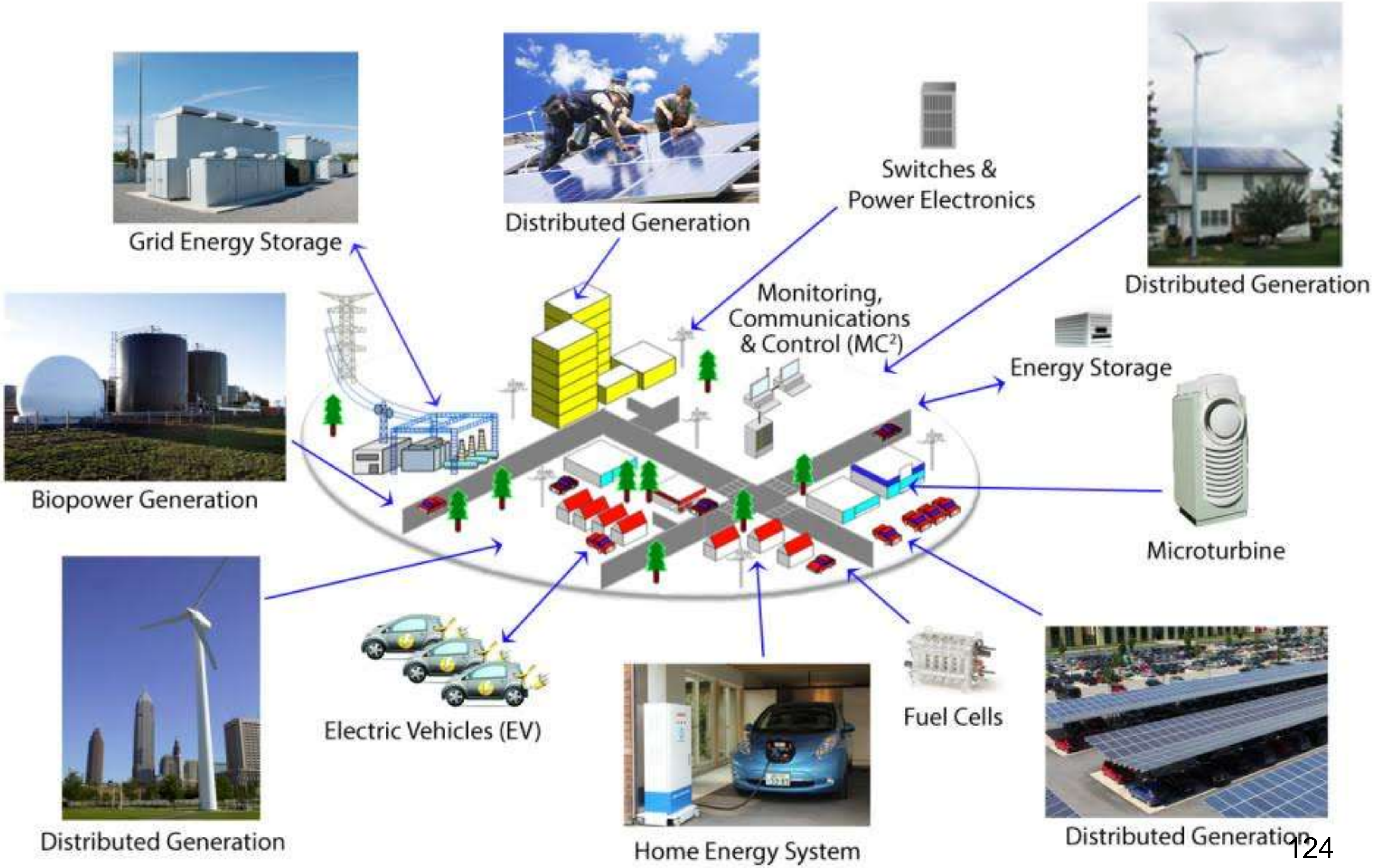
Microgrids avoid single-points-of-failures in the electricity grid, thus increasing the reliability and security of electricity supply to the end-users.

Additionally, they allow higher penetration of renewables



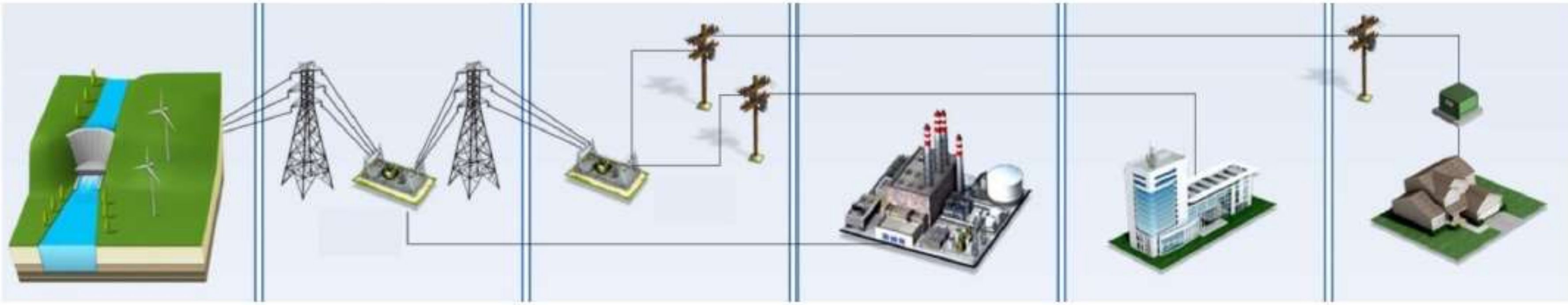
A smaller electricity grid with access to all the essential assets of a larger grid such as generators, transmission lines, substations and switchgear.

Smartgrid will have diverse generating sources with high percentage of renewables



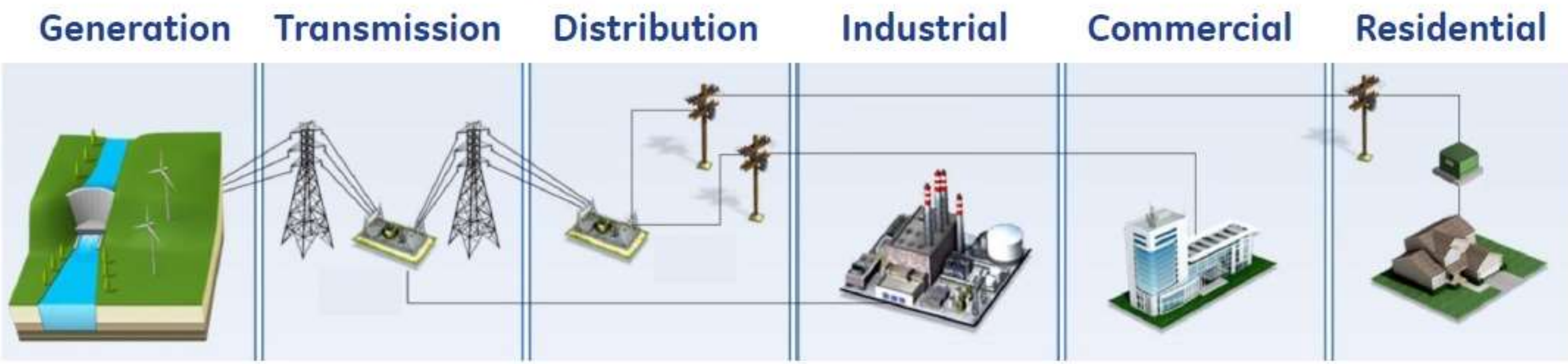
Smart Grid Opportunities

Generation | Transmission | Distribution | Industrial | Commercial | Residential



- Renewable Energy
- Integrating Renewables
- Distributed Generation
- Electric Vehicle Integration
- Flexible Generation
- Cyber Security
- Energy Storage
- Demand Response
- Dynamic Reactive Power
- Wireless Comms
- Distribution Automation
- Smart Meters
- Flexible Transmission
- Wide Area Measurements
- Substation Automation
- Home Energy Monitoring

Smart Grid Opportunities

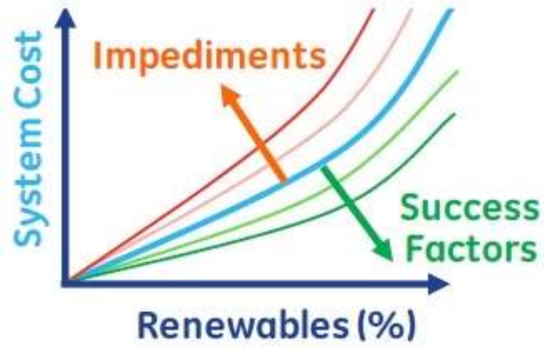


Renewable Energy	Integrating Renewables	Distributed Generation	Electric Vehicle Integration
Flexible Generation	Cyber Security	Energy Storage	Demand Response
Dynamic Reactive Power	Wireless Comms	Distribution Automation	Smart Meters
Flexible Transmission	Wide Area Measurements	Substation Automation	Home Energy Monitoring


Integrating Renewables
How feasible is it to supply 30% of our energy from wind power?
5

Integrating Renewables
Wind Power Can Be Accommodated

GE Renewables Integration Studies
10 yrs of study, examining 4% to 30% renewables, by energy



Success Factors

- Operational Strategies
  - Wind forecasting, Reserves
- Flexible generation
- Spatial diversity of wind & solar
- Grid-friendly wind & solar

Impediments

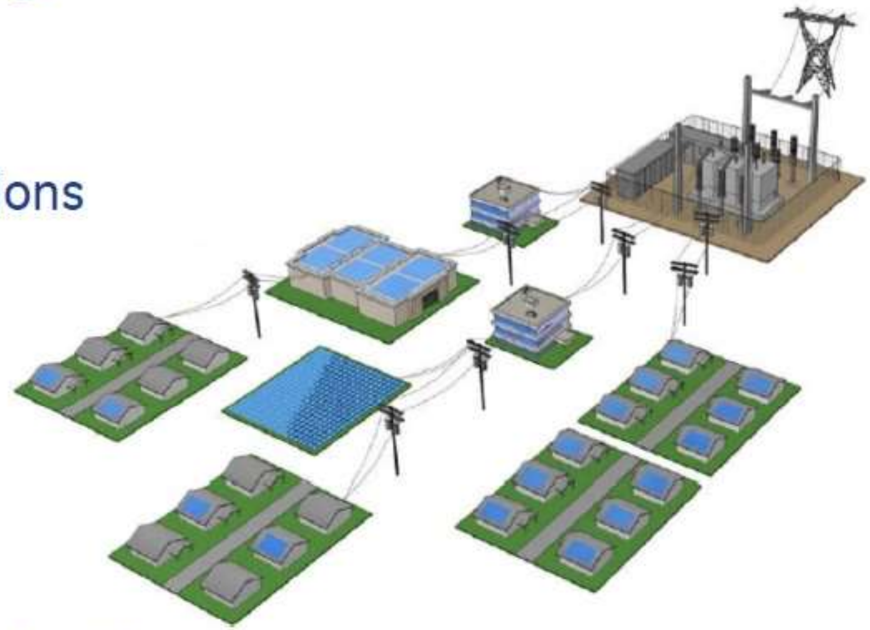
- Lack of transmission
- Lack of control area cooperation

All grids can accommodate substantial levels of renewable energy ... Success Factors & Impediments unique to each system


Distributed Generation
Generation situated closer to the loads …
What are the challenges and opportunities?
7

Distributed Generation
Enhance Reliability and Economics

- **Economies of scale drive towards large well-integrated grids**
- **Key drivers for DG**
  - Incentives ... Solar PV in some regions
  - Increase efficiency ... Combined Heat/Power
  - Reliable back-up power
  - Reduce peak demand charges
  - Use local fuel (biogas, sun, wind)
  - May be only option in undeveloped grids



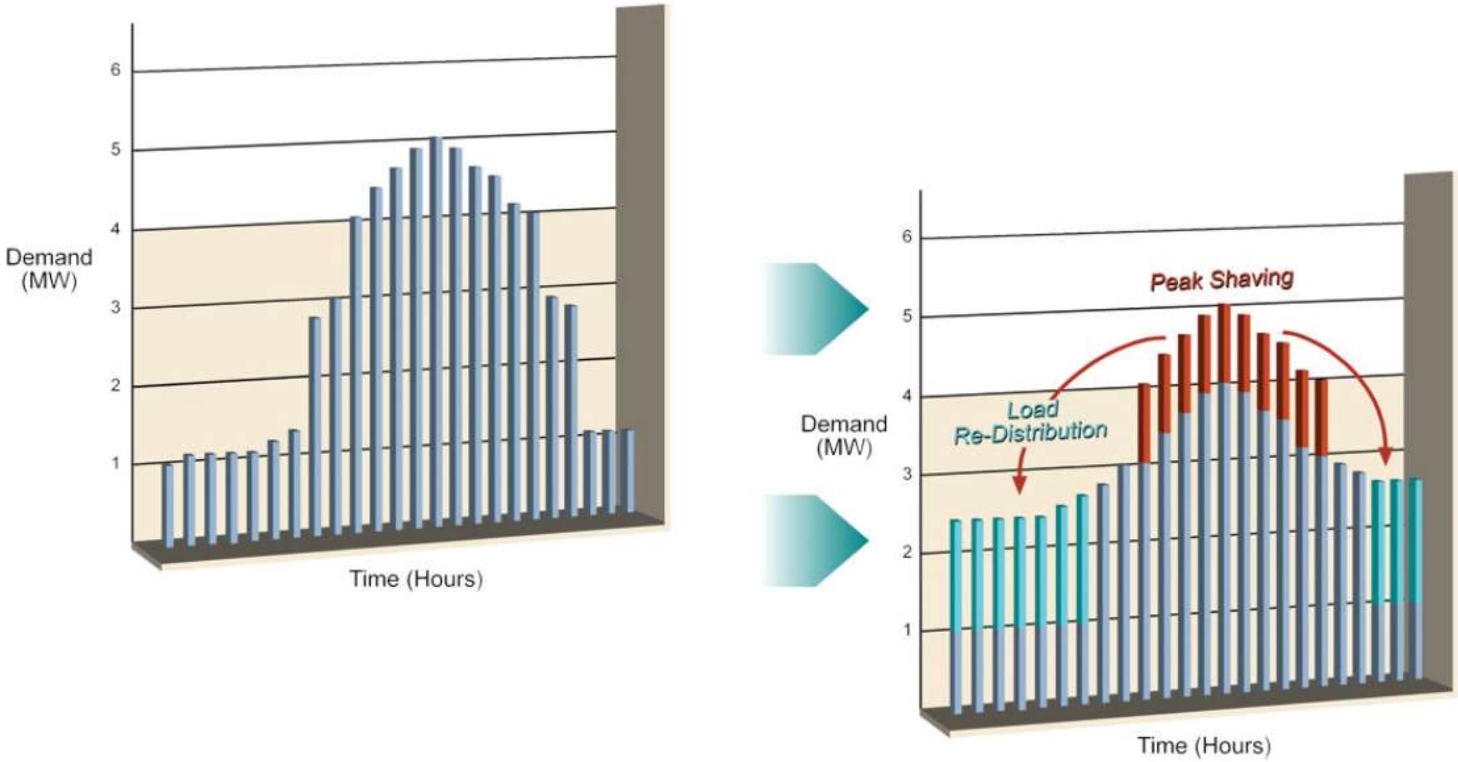
DG will likely play a greater role in all grids, particularly where reliability matters

Demand Management

The industry has focused on
the supply-side ...
What can be offered by the
demand-side?

Demand Side Management

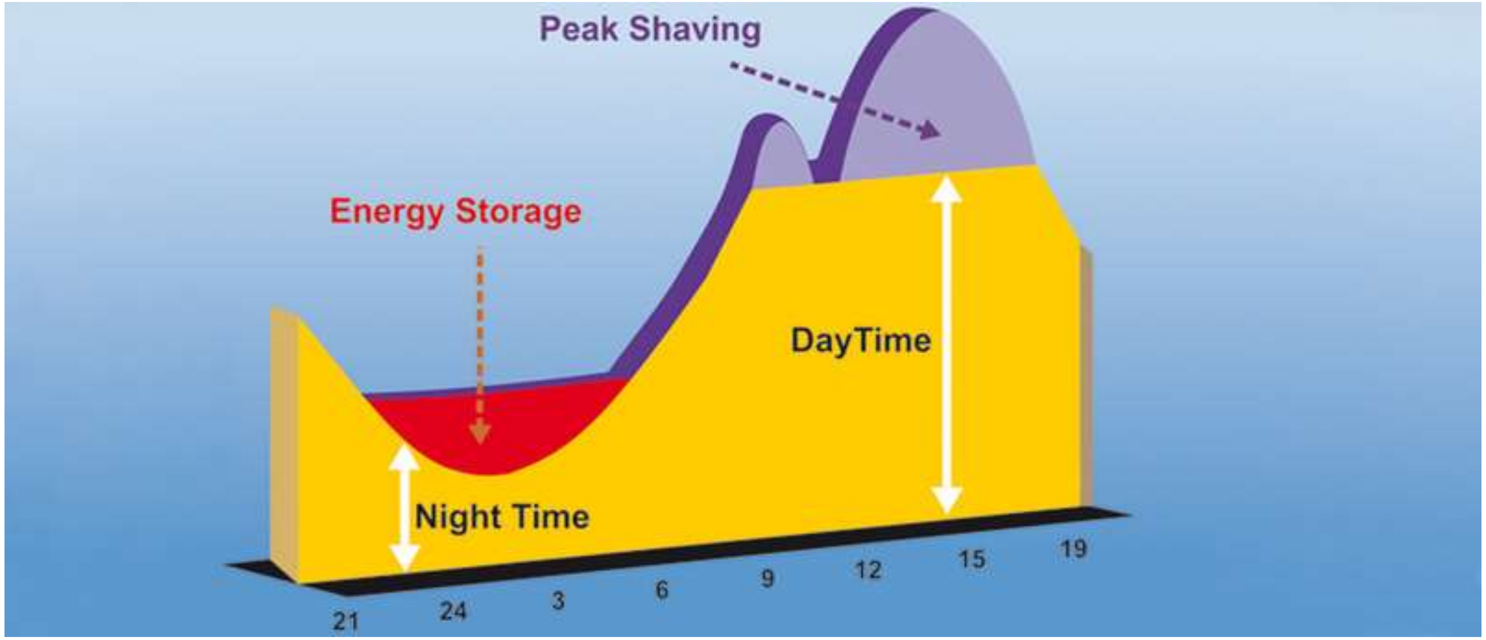
Demand side management (**DSM**), is the process of balancing the supply of electricity on the network with the electrical load by adjusting or controlling the load rather than the power station output.



Demand Side Management

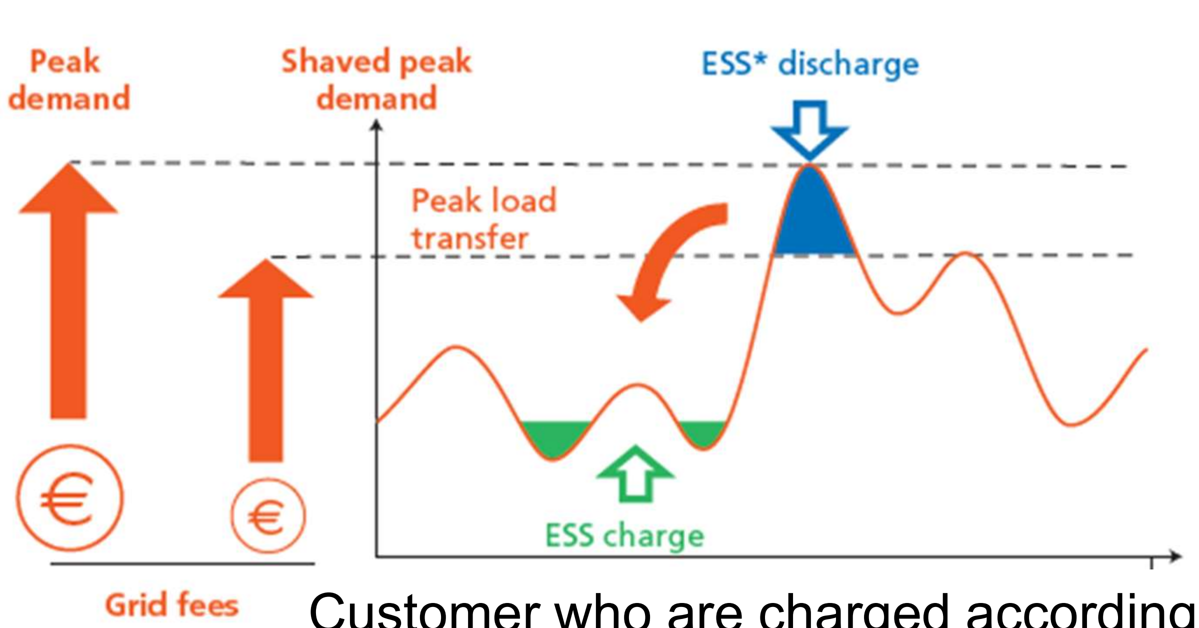
Demand side management (**DSM**), is the process of balancing the supply of electricity on the network with the electrical load by adjusting or controlling the load rather than the power station output.

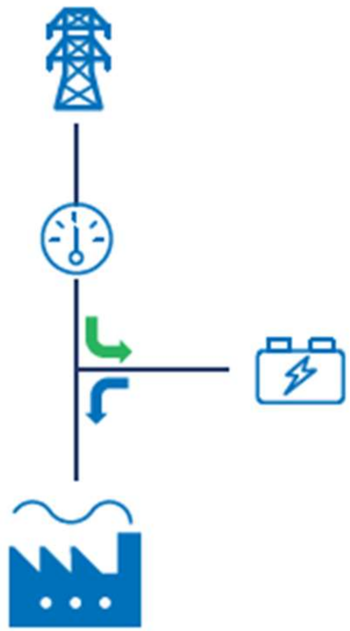
Energy storage can be used for load management and reduce demand for electricity during peak usage times



Demand charge reduction

Reducing the cost of electricity for large industrial/commercial customers

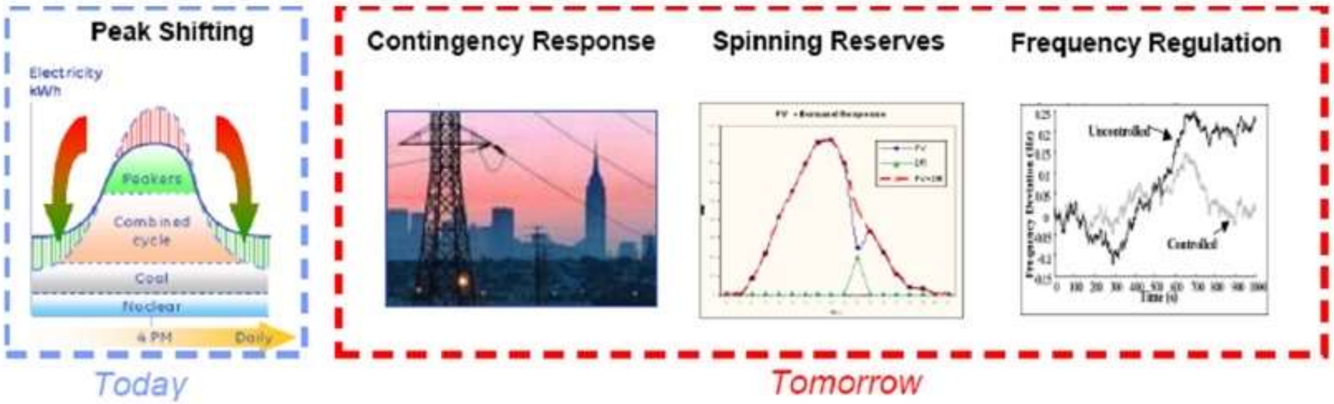




Customer who are charged according to their peak demand can make huge savings on their electricity bills

Demand Management
Significant Untapped Potential

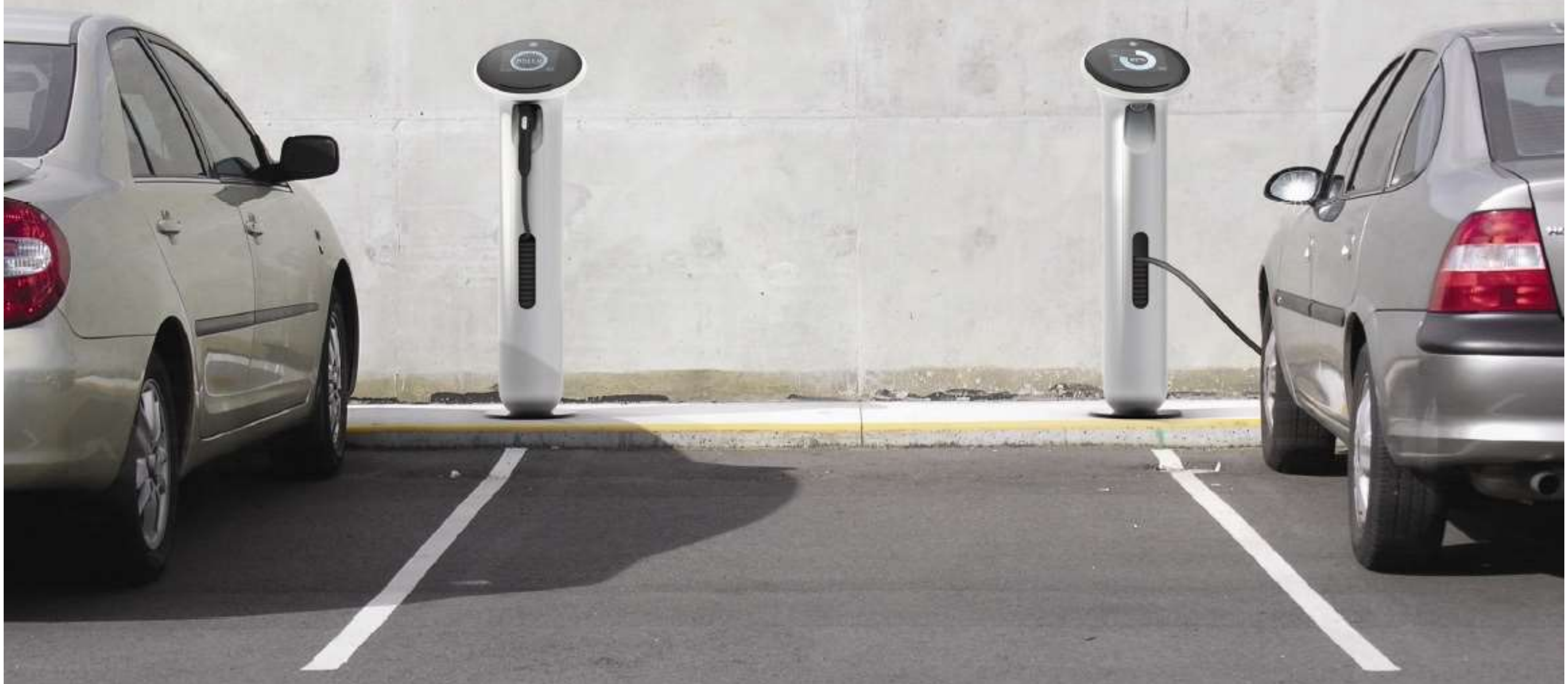
- Demand can also provide grid services
- Metering, Home Software, Home Devices, Utility Software, Communications
- Approaches ... Direct load control, price schedules & signals
- Opportunities ... Ancillary services, T&D equipment deferral



Demand management offers a potentially low cost approach to meet capacity needs, while enhancing grid flexibility

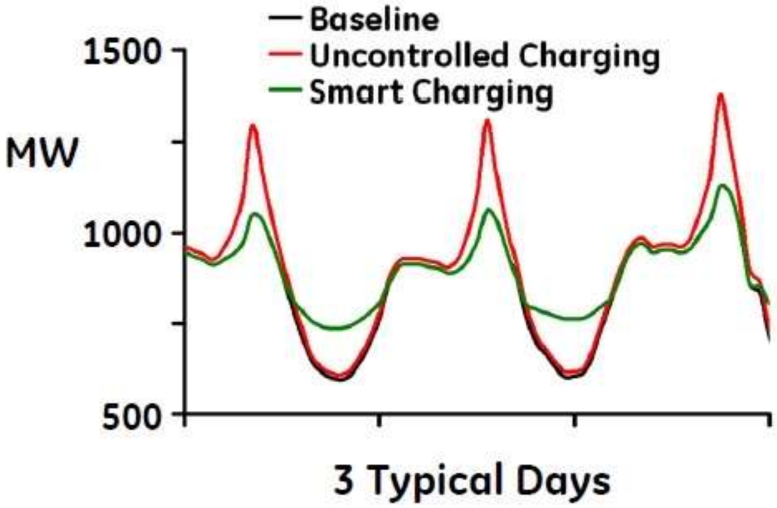
Electric Vehicle Integration

What if electric vehicles (EVs) or plug-in EVs constituted 10% of the vehicle fleet ... What are the challenges and opportunities?

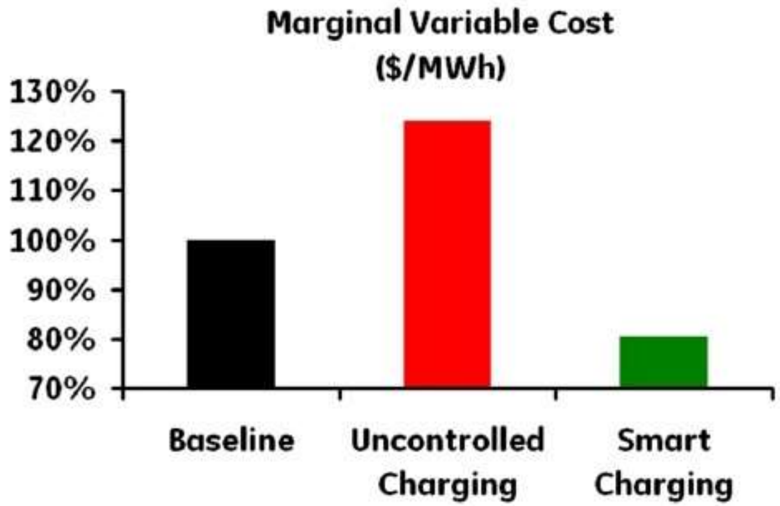


Electric Vehicle Integration
"Smart" Vehicle Charging is Valuable

If 10% of the vehicle fleet were replaced with EVs, peak load could substantially increase



The marginal cost of serving the EV load is much lower when the EVs are "smart" charged

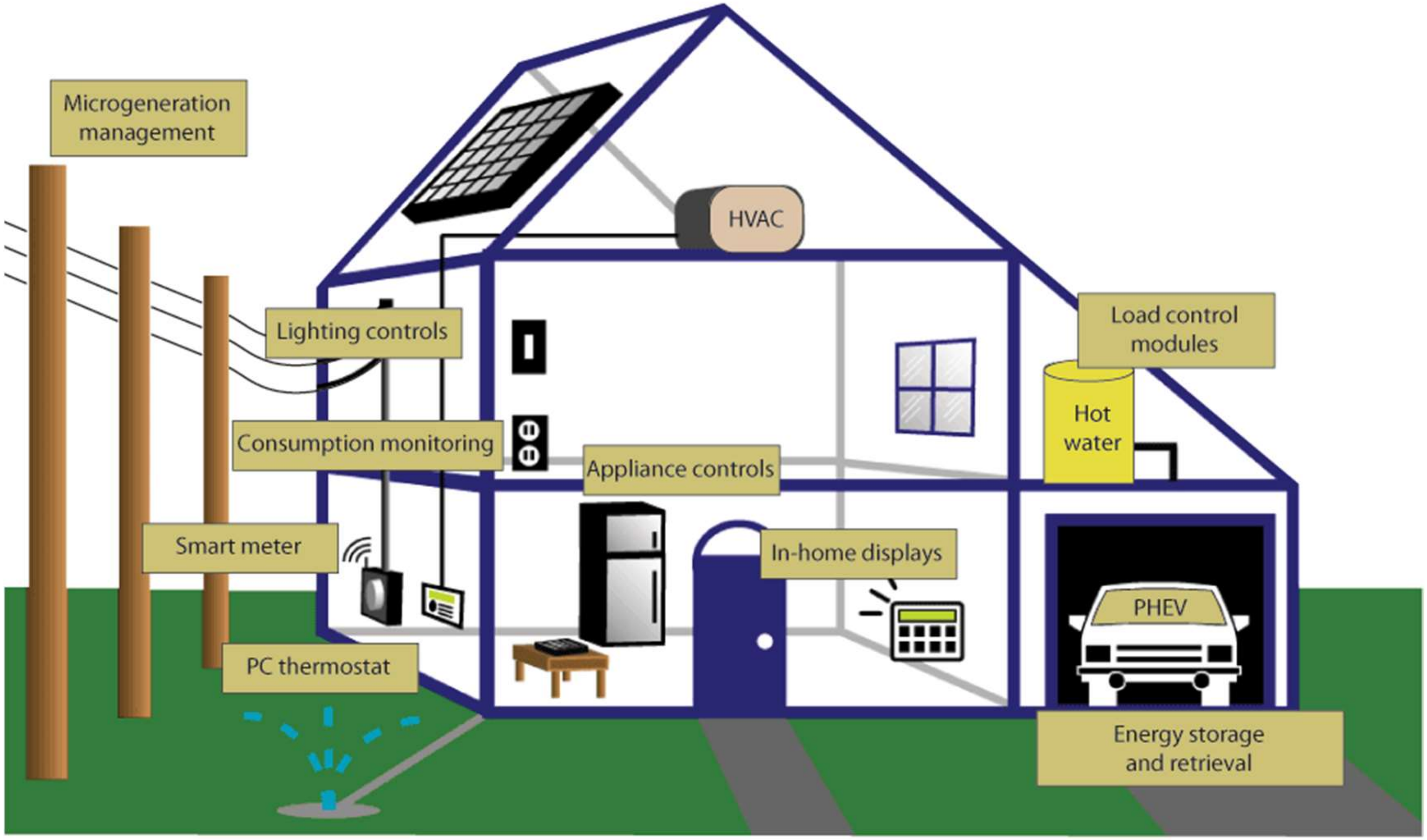


EVs will grow the load ... Charging strategies are valuable ...
Savings can be used to provide incentives & build infrastructure

Source: Manz, Miller, Hinkle. "Integrating Electric Vehicles into the Power System." CIGRE Symposium, Bologna, Italy, 09/2011

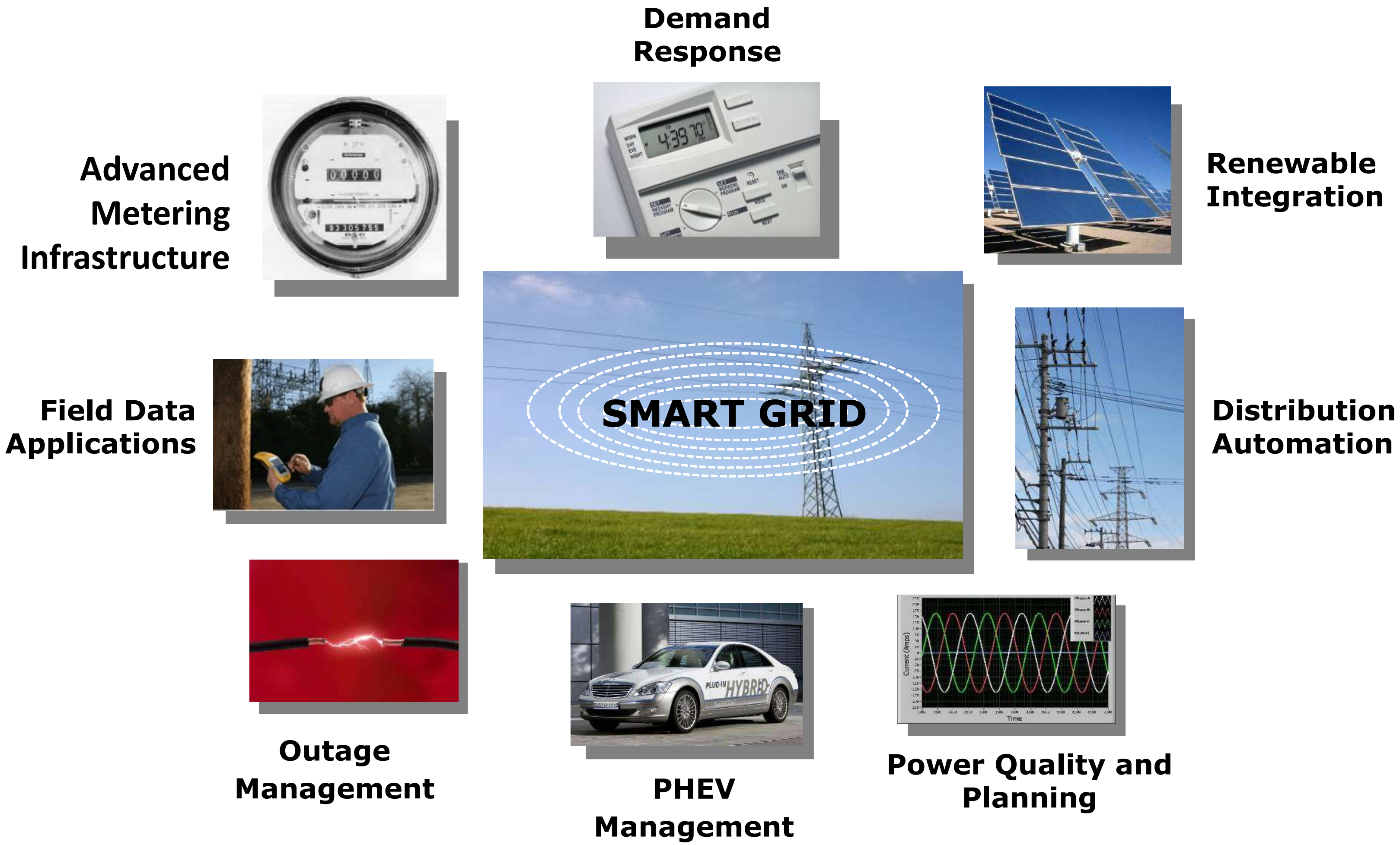
Energy Management in a Smart Home

- Residential energy management to facilitate consumer adoption of energy conservation and management options



The home-area network (HAN) consists of the smart meter with its communications link back to the utility and the connections to the HVAC thermostat as well as the many appliances and other devices whose energy is to be monitored and controlled. Solar panels or the batteries in the plug-in hybrid electric vehicle (PHEV) can provide "microgeneration" energy back to the grid. (courtesy of Parks Associates)

Smart Grid



Distributed Intelligence, Automated Controls, advanced sensing technologies, and Integrated Broadband Communications

How the Smart Grid is Key to a Sustainable Energy Future?

1. Key enabling technology

Smart grids will play a significant role in enabling:

- nearly all clean energy technologies, including renewables
- electric vehicles, and
- energy efficiency

2. Deployment of new electricity infrastructure in developing countries and emerging economies.

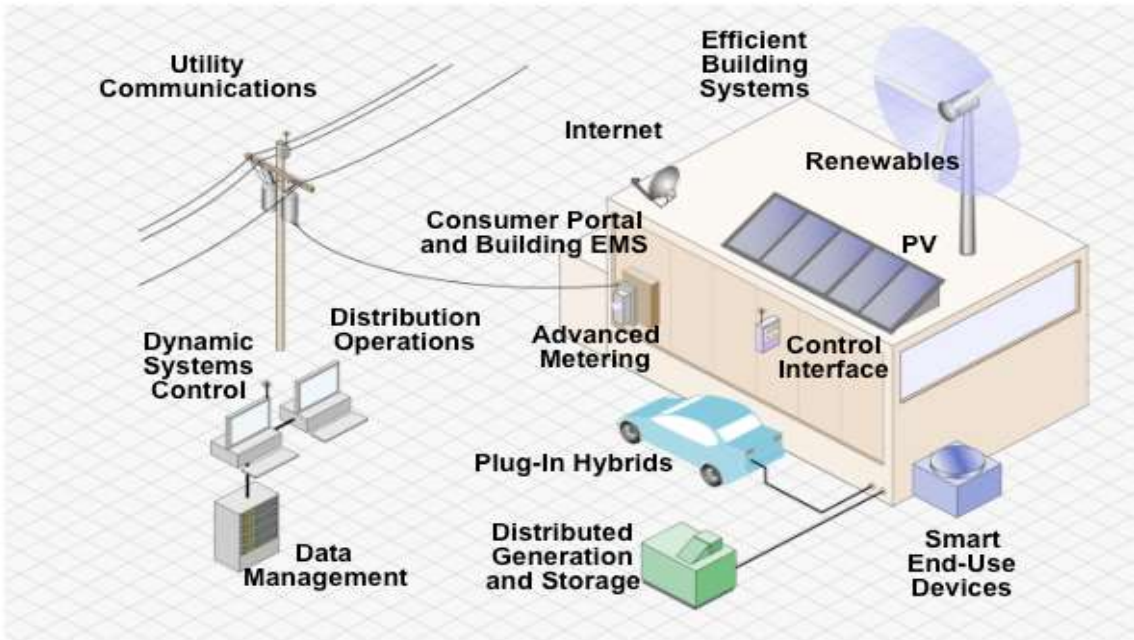
3. As well as enabling more efficient operations, smart grids can also help to keep downward pressure on the cost of electricity

Current challenges to Smart Grid Widespread Adoption

- Lack of comprehensive, long-term and integrated Smart Grid strategies and roadmaps tied to quantifiable benefits
- Substantial capital investment required up front
- Interoperability and the need for faster, more comprehensive development of standards, including physical and cyber security

Not created all at once – will *evolve over many* years

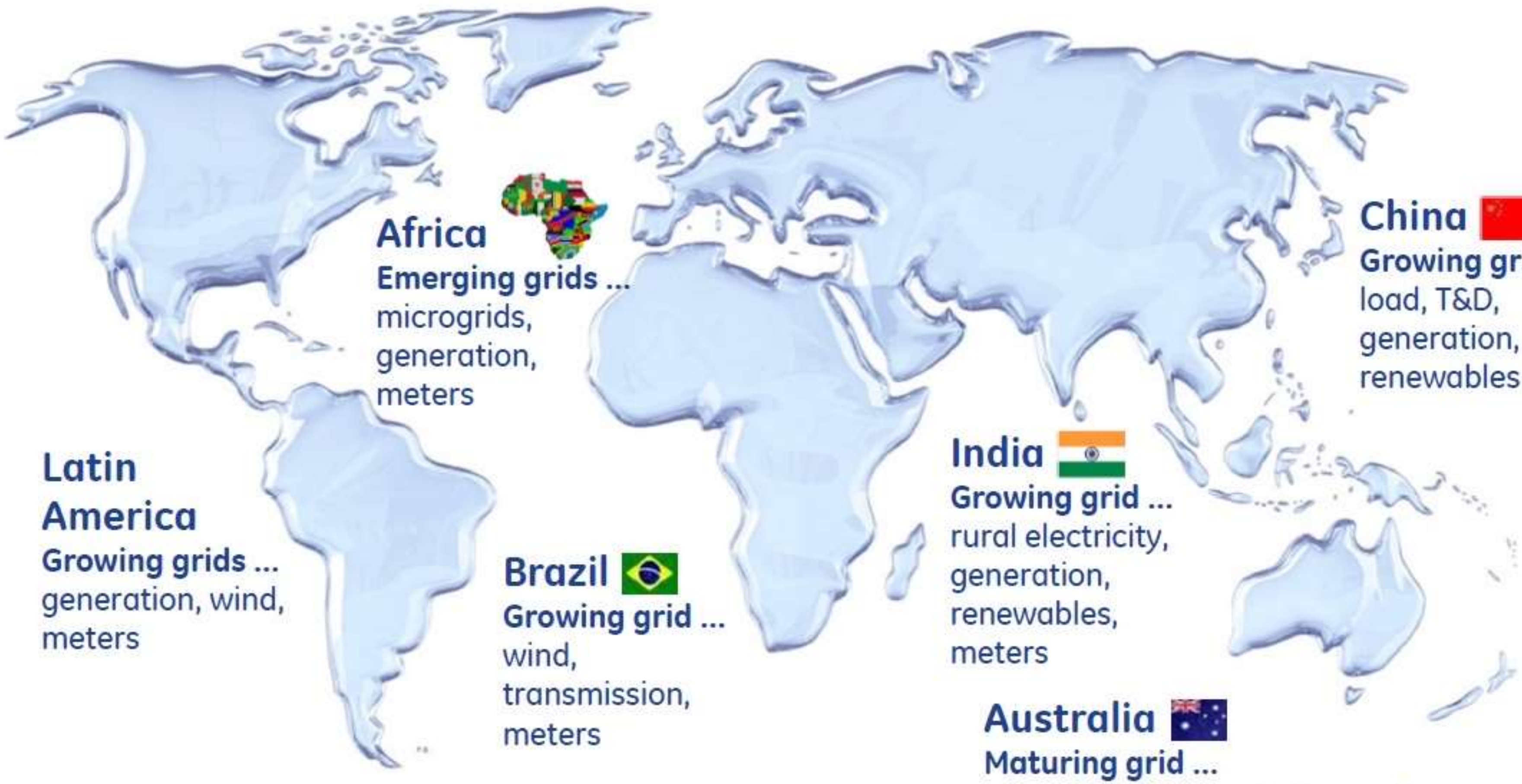
Created through the incremental deployment and integration of *system intelligence*



Global Smart Grid Trends

North America & Europe
Maturing grids ... reliability, aging T&D, active distribution, renewables, meters, demand response, EVs

Every region has unique challenges and opportunities



Africa
Emerging grids ... microgrids, generation, meters

China
Growing grid ... load, T&D, generation, renewables

Latin America
Growing grids ... generation, wind, meters

India
Growing grid ... rural electricity, generation, renewables, meters

Brazil
Growing grid ... wind, transmission, meters

Australia
Maturing grid ... renewables, transmission, meters

Developed Grids … North America/Europe
Decades of Grid Evolution

- Changing generation mix … Transitioning from coal to natural gas and renewables; greater need for flexible generation
- Generally well-developed/integrated T&D … Infrastructure aging
- Heavy demands on transmission … Lines reaching thermal or stability limits and transmission-build out has not kept pace
- Increasingly active distribution systems … Emergence of demand response, distributed generation … Need for advanced controls
- Slow, but steady emergence of electric vehicles … A significant new load

Project: EU-SysFlex (2017-2021)

- System operation and **flexibility** solutions for **integrating 50% renewables by 2030**
- Germany: Flexibility of active and reactive power from HV grid to EHV grid
- Italy: Service Provision from resources connected to the MV DSO network
- Finland: Provision of flexibility services from distributed LV or MV assets
- Portugal: Flexibility Hub using DSO grid connected resources
- Portugal: Virtual Power Plant
- France: Aggregation approaches for the provision of multi-services
- Estonia: Cross-border data exchanges
- Ireland and Northern Ireland: Qualification Trial Process and breaking barriers

Africa
Population Growth and Industrialization

- Inadequate generation, high cost of electricity, reliability challenges in some regions
- Distribution … High losses, long feeders, voltage fluctuations, cable overloads
- Long distance transmission pass over small load centers
- **Opportunities**
  - Wind, solar, and gas … Complements Hydro
  - Transmission … Long distances between supply/demand
  - Rural electrification … Distributed Generation, Microgrids, Meters

Project: Ghana's Energy Development and Access Project (2007-2022)

- To improve the operational **efficiency** of the electricity distribution system and increase the population s access to electricity.
- Improving access to power through off-grid solar energy and mini-grids
- Bringing renewable, off-grid energy to communities

India

Developed & Developing Grids

- Lack of generation and transmission ... 30% increase in generation & $125B transmission expected in next 5yr
- Frequent power shortages in some regions ... Demand often exceeds supply ... Circulating blackouts
- Lack of electricity in some rural areas ... India is 65% rural; 100,000 villages without electricity
- **Opportunities**
  - Wind power ... Policy
  - Transmission ... Wide Area Monitoring, Flexibility
  - Technical & commercial losses ... Distribution Automation, Meters
  - Rural electricity ... Distributed Gen, Microgrids

Project: Smart Meter Installation Begins in Rajasthan (Ongoing)

- Energy Efficiency Services Limited (EESL) has issued a tender for the procurement of 188,000 **smart meters** for deployment in two areas of Rajasthan.
- To have a sustainable impact by **system monitoring** on the distribution sector.
- Optimize the operational performance by increasing the billing and collection efficiency
- Reduce the operation and maintenance cost
- Enhance the quality of service
- Provide the consumers with demand-side management (DSM) options

Brazil
Growing Economy & Infrastructure

- Load is growing … 104GW today; adding 64GW in next 10 yr … Growth in wind and hydro
- Long-distance transmission needed … Hydro 1,500 miles away from large load centers
- Reliance on hydro power … Droughts threaten hydro depletion
- **Opportunities**
  - Smart Meters … 65M to be replaced in Brazil in 10yr
    - Time-of-use electric rates … Manage peak load growth
    - Monitoring … Address commercial losses
  - FACTS / Series Compensation, High Voltage DC … Continued growth
  - Integration of Wind/Hydro … Advanced wind turbines, wind can help preserve hydro in hot/dry seasons

Project: Brazil's Eletrobras Distribution Rehabilitation Project (2011-2017)

- Smart-grid network equipment: reclosers, capacitors, etc.
- Network extensions: including adding unconnected customers
- Advance metering technology: with telemetering capabilities of thousands of kilometers for large consumers
- An updated customer database and proper project management procedures

China

Rapid Grid Expansion Underway

- Power shortages ...
- Wind concentrated in the North
- Long-distance transmission
  ... High Voltage AC/DC
- Significant coal ... >300GW in past 5 years
- **Opportunities**
  - Transmission/Substation Monitoring
  - Interconnectivity ... IT & Wireless
  - Wind forecasting & operations
  - Long-term growth in EVs and charging infrastructure
  - Distribution system build-out

Wind Concentrated in North

More Transmission Needed

Project: Smart Power Grid Operation with AI (Ongoing)

- China Southern Power Grid (CSG) widely uses **smart robots** for the daily operation and maintenance of power grids in 5 provinces in recent years
- Leverage 5G, AI, cloud computing techniques, etc.
- Realize intelligent, reliable, efficient and fully automated power system operation

Smart Grid Projects in Singapore

Singapore – Recent announcement of Smart Grid trial

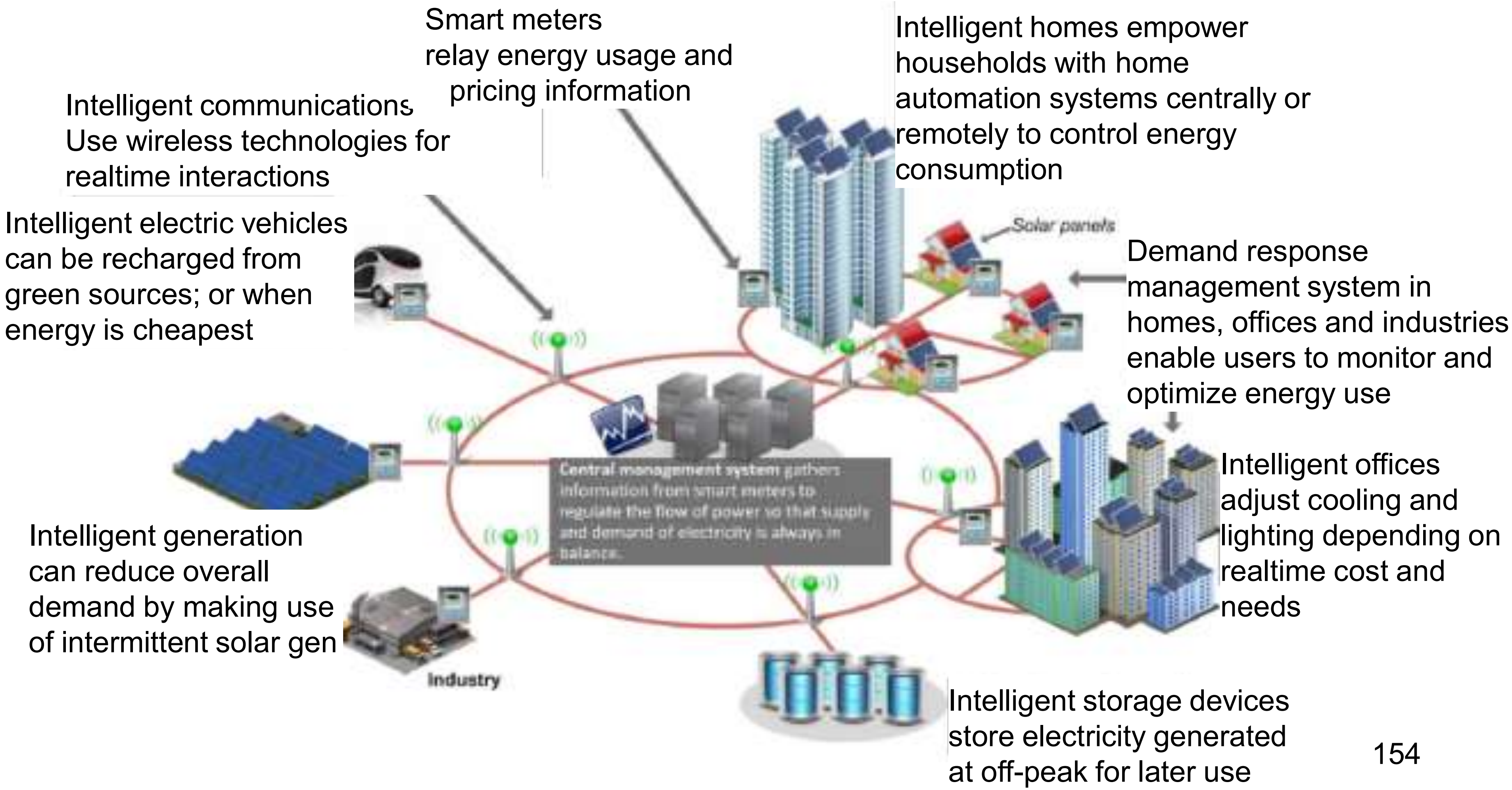
The pilot project includes the installation of more than 4,500 smart meters in residential, commercial and industrial locations to test and evaluate workable solutions

- Includes smart meters
- Grid side & Customer side
- EVs
- Integration of intermittent generation

Singapore grid already deploys advanced Supervisory Control and Data Acquisition (SCADA)

Smart Grid in Singapore
– Intelligent Energy System (IES) project

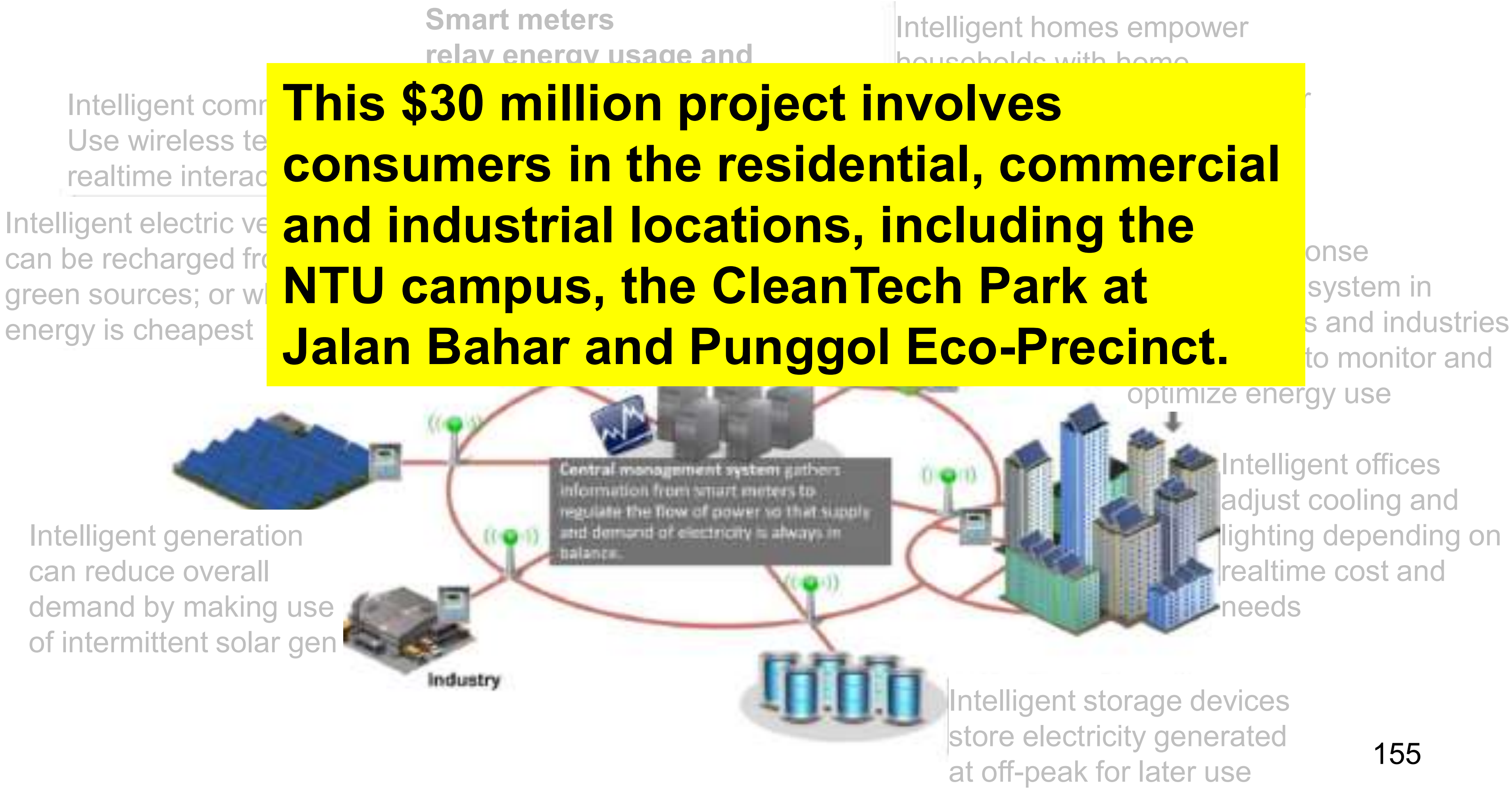
The IES Pilot project conceptual overview – An energy ecosystem connecting intelligent homes, vehicles, communities, electricity network sensors and sources of green generation to promote reliability, sustainability and energy efficiency



Smart Grid in Singapore
– Intelligent Energy System (IES) project

The IES Pilot project conceptual overview – An energy ecosystem connecting intelligent homes, vehicles, communities, electricity network sensors and sources of green generation to promote reliability, sustainability and energy efficiency

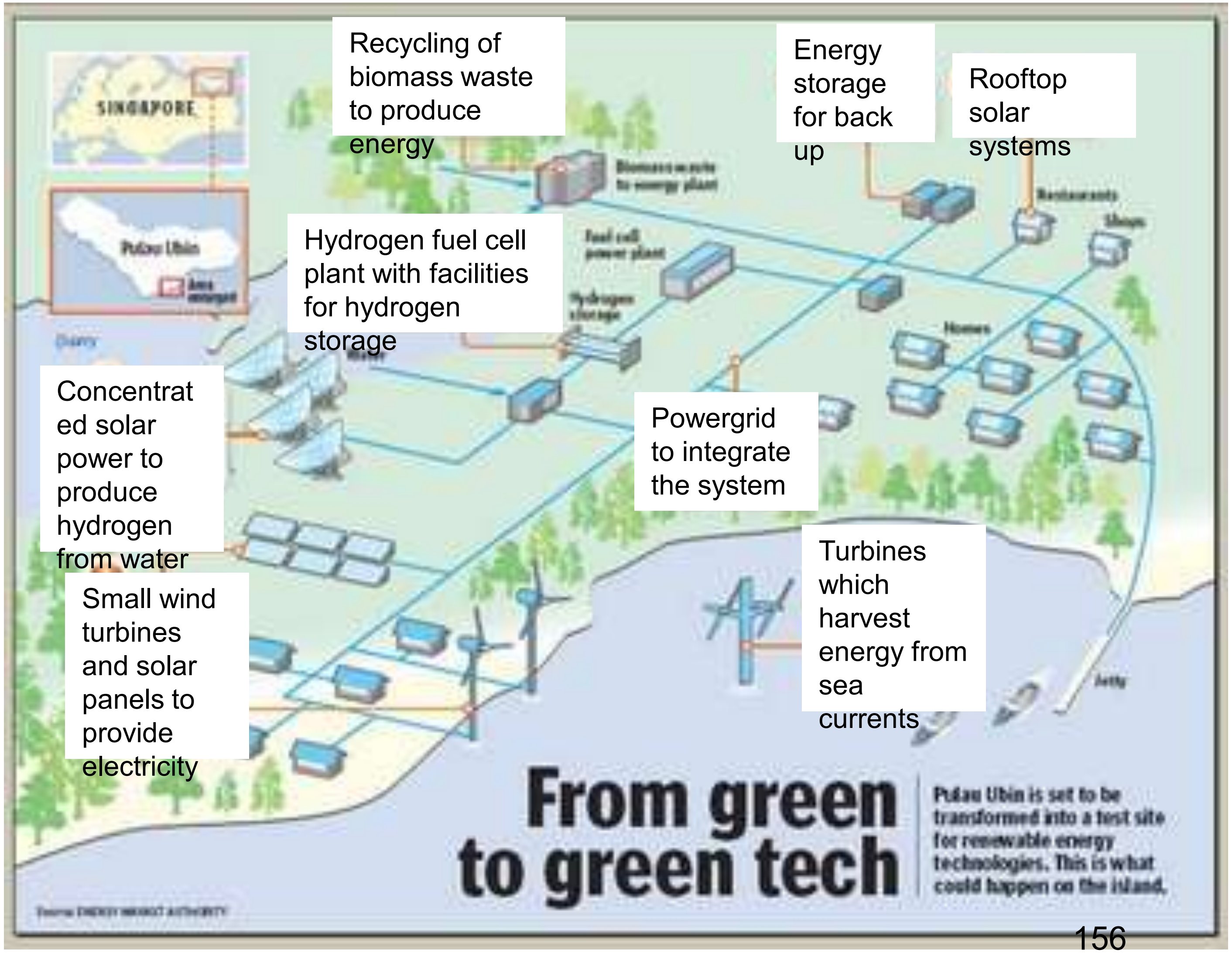
This $30 million project involves consumers in the residential, commercial and industrial locations, including the NTU campus, the CleanTech Park at Jalan Bahar and Punggol Eco-Precinct.



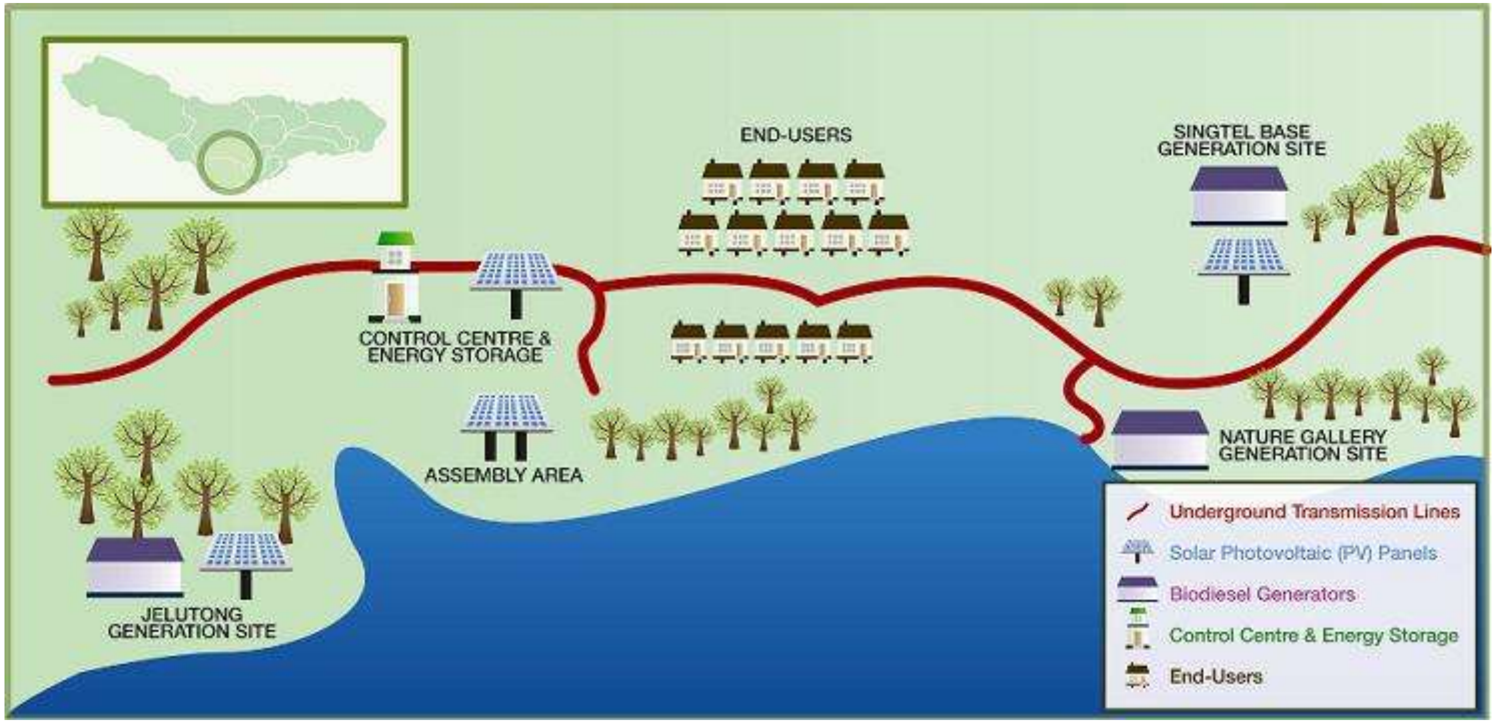
Smart Grid in Singapore

– Pulau Ubin Microgrid project

The Test-bed aims to assess the reliability of electricity supply within a micro-grid infrastructure using intermittent renewable energy sources such as solar photovoltaic (PV) technology.



Pulau Ubin Microgrid project



The Micro-grid Test-bed will bring about more cost-competitive and cleaner electricity, with improved scalability and reliability for both residents and businesses in Pulau Ubin.

- **Cleaner energy**
- **Reliable electricity supply**
- **Cost-competitive electricity**
- **Scalability**

Smart Grid in Singapore
– EPGC Microgrid and Distributed Energy facility

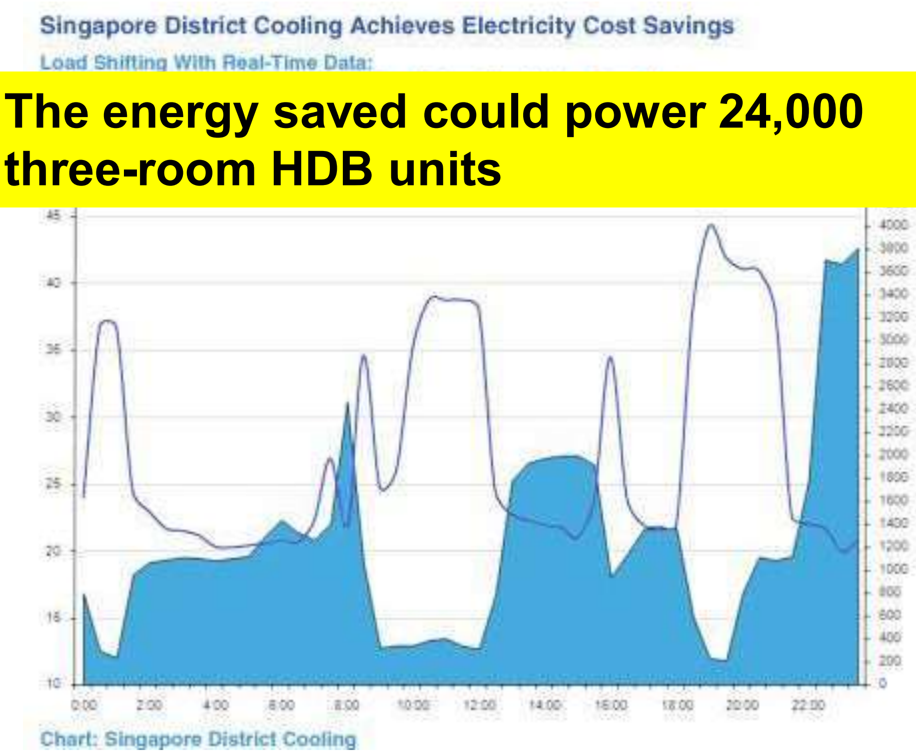
World's largest pilot smart grid with a capacity of 1MW.

$38 million power grid project on Singapore's Jurong Island.

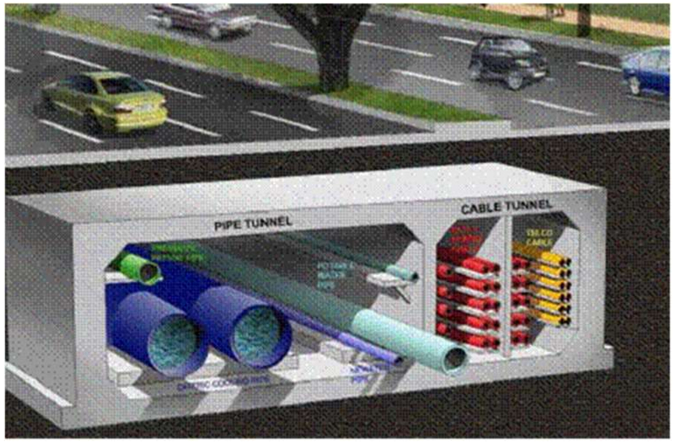
Electricity from renewable energy sources like solar and wind also fed into the grid system.

Singapore District Cooling

- An example of demand side management in Singapore.
- Use electricity to charge thermal energy storage system.
- Shift the charging period during low price and discharge during high price. https://www.youtube.com/watch?v=XM08h6xI9Rw
- World's largest cooling plant by capacity!
- District cooling is an energy-efficient and cost-effective method to provide buildings in the area with an optimal indoor climate.



The energy saved could power 24,000 three-room HDB units



NUS SERIS Project – Advanced Solar Power Forecasting for Incorporating Large-scale Solar PV Systems

Meteorological Service Singapore
7-hours prediction of common weather parameters

Meteorological Service Singapore
7-hours prediction of irradiance (aggregate and 2D)

via secure VPN tunnel

Energy Market Authority – Smart Energy, Sustainable Future
Receives 24/7 irradiance data

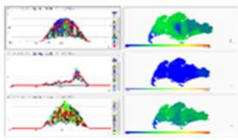
Energy Market Authority – Smart Energy, Sustainable Future
Generation and load balancing for dispatch + EMC

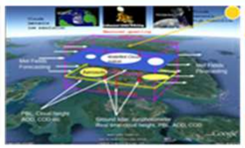
SERIS – Solar Energy Research Institute of Singapore | **CRISP** – National University of Singapore | **NUS** – National University of Singapore

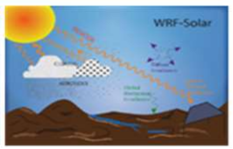
Solar Irradiance Forecasting (7-hours in increments of 5-30min) WP1

Methodologies

5 - 60min	1hr - 3hrs	2 - 7hrs
Statistical methods	Satellite hybrid modelling	Satellite + WRF Solar for irradiance





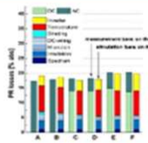


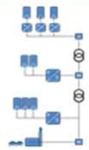
SERIS – Solar Energy Research Institute of Singapore | **NUS** – National University of Singapore

Conversion to power output + Grid impact analysis WP2

Methodologies

Conversion	Grid impact
PV system modelling	Power system simulations



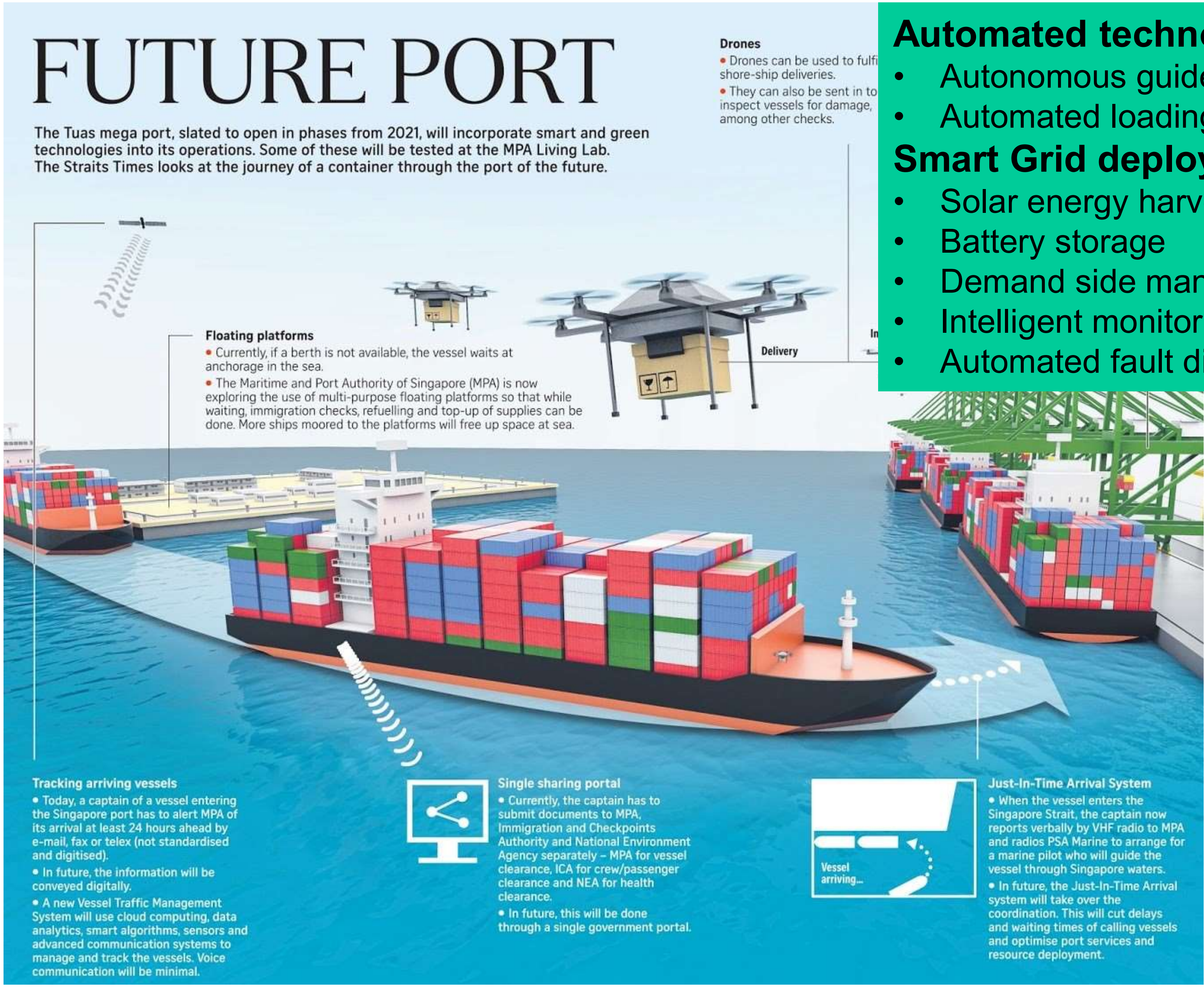


YYT(5 Please update EPGC's logo.
Yi Yun TEO (EMA), 30/1/2020

YYT(6 Please also update other aspects of this chart if necessary.
Yi Yun TEO (EMA), 30/1/2020

Envision-NUS Project for PSA

AIoT-Enabled Smart Grid Applications for Sustainable and Resilient Digital Ports



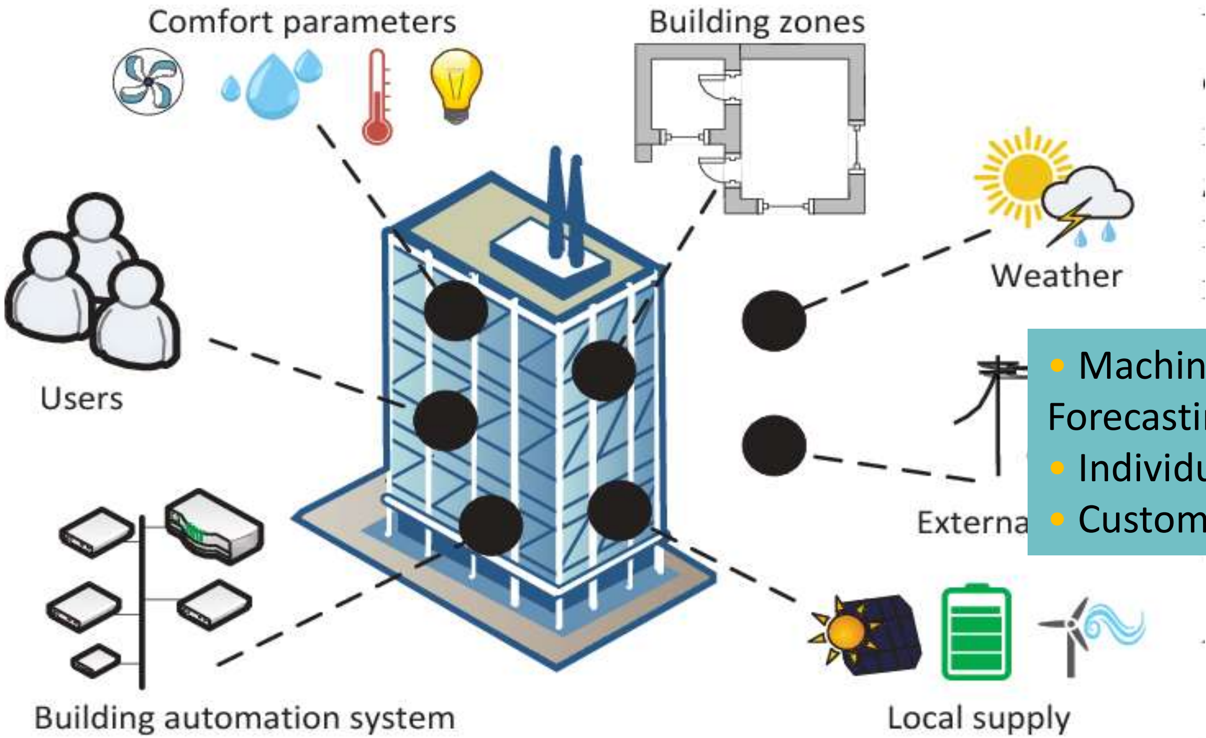
Automated technology

- Autonomous guided electric vehicles
- Automated loading/unloading

Smart Grid deployment

- Solar energy harvesting
- Battery storage
- Demand side management
- Intelligent monitoring and control
- Automated fault diagnosis

NUS-Resync Project: AI based and Data Analytics driven DSM Solution



- Machine Learning Based Forecasting
- Individual Asset Analytics
- Customized report

- Real Time Control & Optimization
- Evolutionary Algorithm Optimization
- Multiple Sites Monitoring

Conclusions: Microgrid and Smart Grid

Incorporates

(1) two-way communications,

(2) advanced sensors, and

(3) distributed computing technology

All these three will be essential for more efficient and sustainable energy systems, due to:

- Increased reliability
- Smart power generation
- Greater share of renewable energy generation and storage
- Flexibility in network topology
- Better energy efficiency and load management
- Less redundancy in transmission and distribution lines, and greater utilisation of existing generating capacity

Conclusions

- Global drivers are creating opportunities
  - Economy, security, environment, aging infrastructure, policy
- Technologies emerging to meet global needs
  - Renewables, DG, EVs, Demand Response, Dynamic Reactive Power, Distribution Automation, ...
- Opportunities unique to each region
  - Established Grids ... Coping with changing generation mix, heavy transmission demands, aging infrastructure, active distribution
  - Developing Grids ... Coping with rapid growth in generation and transmission, power shortages in some regions, electrical losses

Technologies emerging to meet the needs of the grids of future ...
Challenges, opportunities, priorities are unique to every region

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Additional Contributions from: General Electric (GE) Company, and China Southern Power Grid (CSG) Company