ELG4126- Sustainable Electrical Power Systems- DGD

Economics of Distributed Resources

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Outline

- DISTRIBUTED BENEFITS
  - **Emissions Benefits**
  - Review

Emissions Benefits

Table 1. Carbon Intensity of Fossil Fuels

	Energy Density (kJ/kg)	Carbon Content (%)	Carbon Intensity (kgC/GJ)
Anthracite coal	34,900	92	26.4
Bituminous coal	27,330	75	27.4
Crude oil	42,100	80	19.0
Natural gas	55,240	77	13.9

- Natural gas emits only about half the carbon per unit of energy when it is burned as does coal.

Emissions Benefits

One approach to calculating carbon emissions from CHP plants is to use the **energy chargeable-to-power (ECP)** measure.

Recall that ECP subtracts the displaced boiler fuel no longer needed from the total input energy, which, in essence, attributes all of the fuel (and carbon) savings to the electric power output.

Example 1. Carbon Emission Reductions with CHP

Q:

Use the ECP method to determine the reduction in carbon emissions associated with a natural-gas-fired, combined-cycle CHP having 41% electrical efficiency and 44% thermal efficiency. Assume that the thermal output would have come from an 83% efficient boiler. Compare it to that of a 33.3% efficient conventional bituminous-coal-fired power plant.

Example 1. Carbon Emission Reductions with CHP

Answer:

$$\text{ECP} = \frac{\text{Total thermal input} - \text{Displaced thermal input}}{\text{Electrical output}}$$

$$= \frac{3600}{\eta_P}\left(1 - \frac{\eta_H}{\eta_B}\right) \text{kJ/kWh}$$

$$\text{ECP} = \frac{3600}{0.41}\left(1 - \frac{0.44}{0.83}\right) = 4126 \text{ kJ/kWh}$$

Using the 13.9-kgC/GJ carbon intensity of natural gas provided in Table 1

$$\text{Carbon chargeable to power} = \frac{4126 \text{ kJ/kWh} \times 13.9 \text{ kgC/GJ}}{10^6 \text{ kJ/GJ}}$$

$$= 0.0573 \text{ kgC/kWh}$$

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Example 1. Carbon Emission Reductions with CHP

- The coal plant has no displaced thermal input, so its ECP is the full

$$\text{ECP} = \frac{3600}{0.333} = 10{,}811 \text{ kJ/kWh}$$

- Using 27.4 kgC/GJ as its carbon intensity from Table 1

$$\text{Carbon chargeable to power} = \frac{10{,}811 \text{ kJ/kWh} \times 27.4 \text{ kgC/GJ}}{10^6 \text{ kJ/GJ}} = 0.296 \text{ kgC/kWh}$$

The efficient CHP combined-cycle plant reduces carbon emissions by 81%.

Outline

- DISTRIBUTED BENEFITS
  - Emissions Benefits
  - **Review**

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Review

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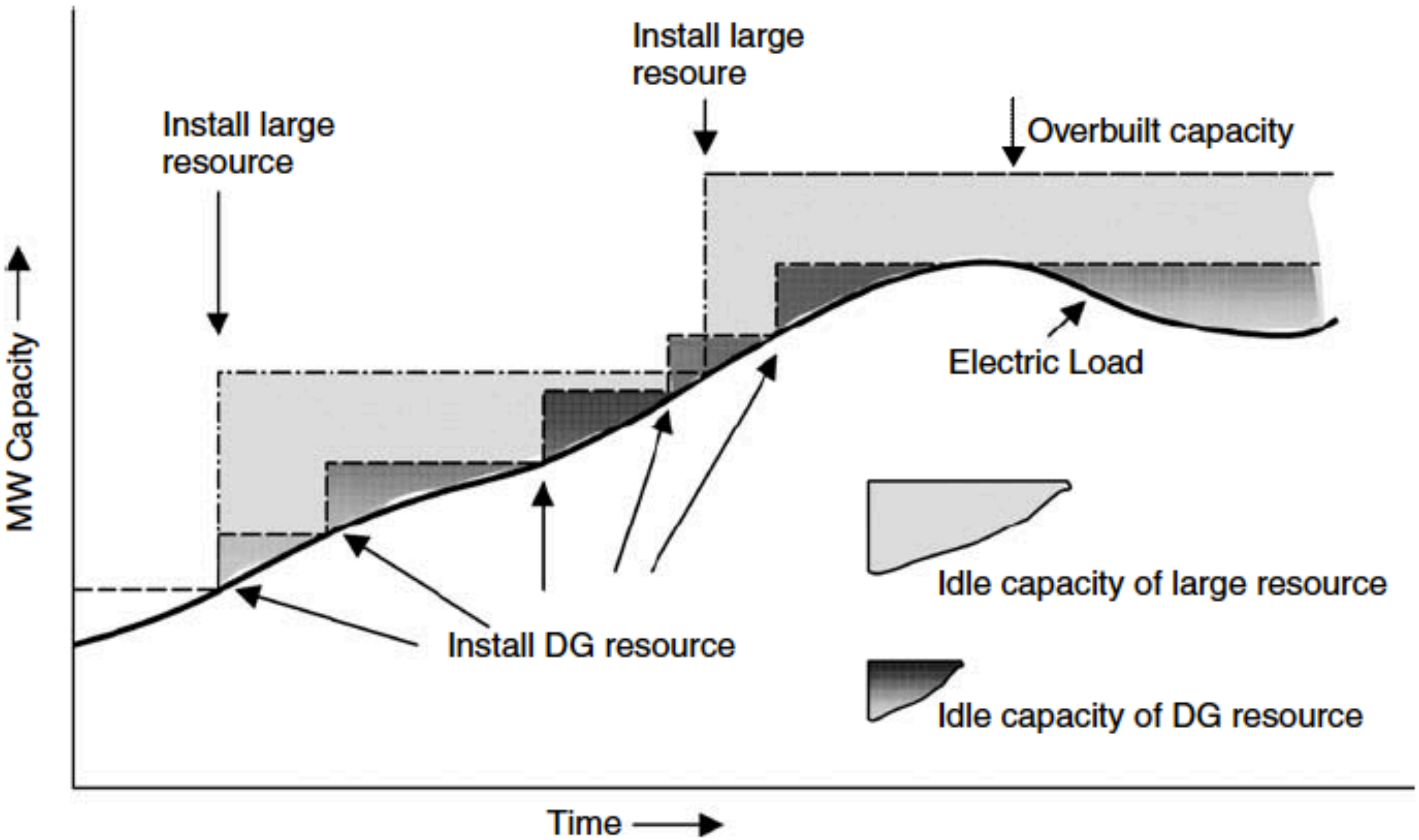
DISTRIBUTED BENEFITS

- Direct energy savings
- Increased fuel efficiency with cogeneration
- ***Option Value****:* Small increments in generation can track load growth more closely, reducing the costs of unused capacity
- ***Deferral Value****:* Easing bottlenecks in distribution networks can save utilities costs.
- ***Engineering Cost savings:*** Voltage and power factor improvements and other ancillary benefits provide grid value.
- ***Customer Reliability Value:*** Reduced risk of power outages and better power quality can provide major benefits to some customers.
- ***Environmental Value:*** Reduced carbon emissions for CHP systems will have value if/when carbon taxes are imposed; for fuel cells, since they are emission-free, ease of permitting has value.

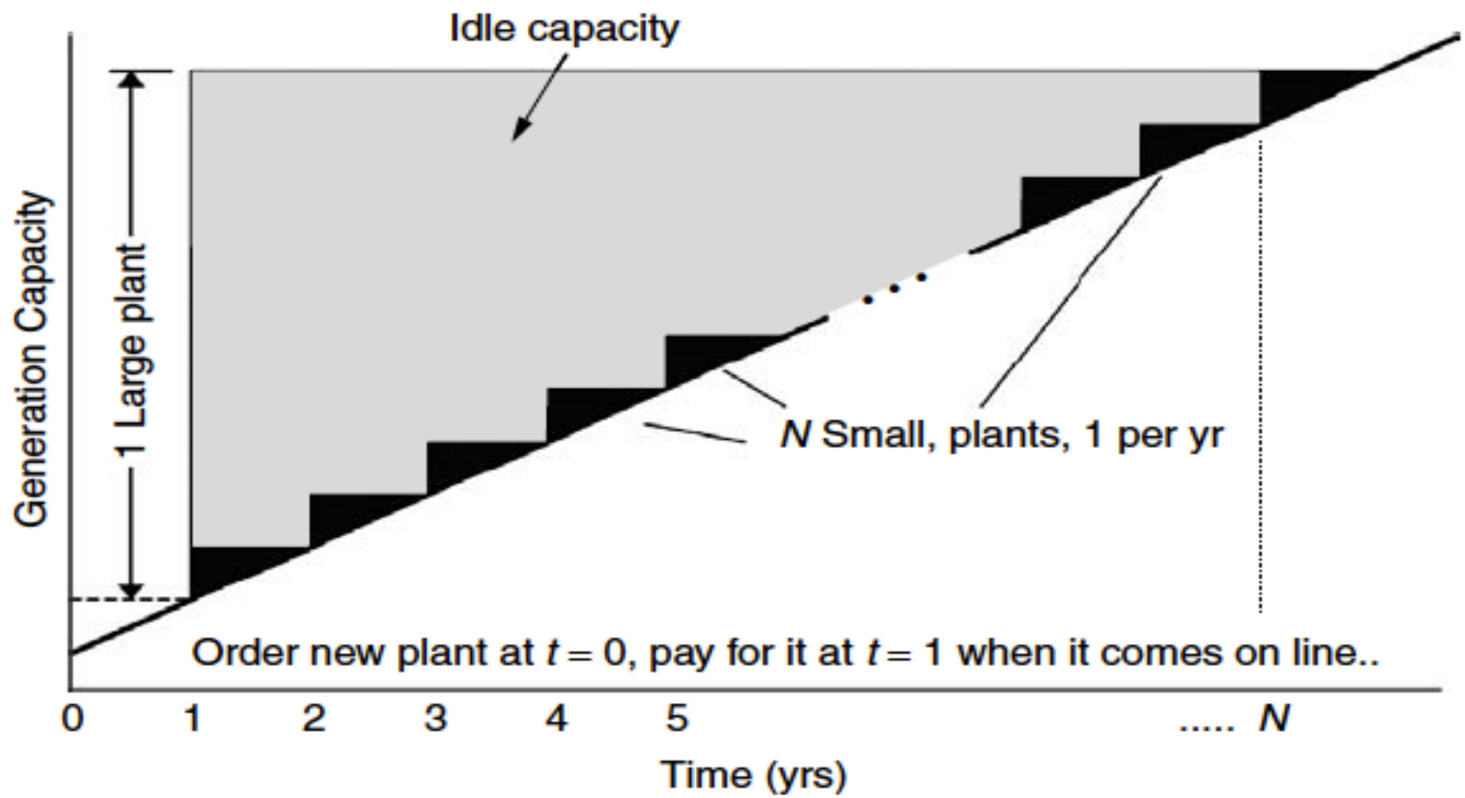
Option Values

Figure 1. Smaller distributed generation increments better track the changing electric load with less idle capacity than fewer, larger plants. Less idle capacity translates into decreased costs.



Option Values

Figure 2. Comparing the present worth of a single large plant capable of supplying N years of growth with N plants, each satisfying 1 year of growth. For simplicity, both are assumed to have 1-year construction lead times



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Option Values

Let

$$\text{Annual growth in demand} = \Delta P \text{ (kW)}$$

$$\text{Cost of a small plant} = P_S \text{ (\$/kW)} \times \Delta P \text{ (kW)}$$

$$\text{Cost of a large plant} = P_L \text{ (\$/kW)} \times N\Delta P \text{ (kW)}$$

$$\text{Discount rate} = d \text{ (yr}^{-1}\text{)}$$

- The present value of the single large plant (PV_L) is its initial cost discounted back 1 year to t = 0:

$$PV_L = \frac{P_L N \Delta P}{(1+d)}$$

Option Values

- For the sequence of N small plants, the present value of N payments of $P_S\ \Delta P$,with the first one at t = 1 year, is given by

$$PV_S = P_S \Delta P \ \mathrm{PVF}(d, N)$$

where PVF(d, N) is the present value function used to find the present value of a series of N equal annual payments starting at t = 1.

- If we equate the present values of the large plant and the N small ones, we get

$$\frac{P_L N \Delta P}{(1+d)} = P_S\ \Delta P\ \mathrm{PVF}(d, N)$$

Option Values

- So

$$\frac{P_S(\$/\text{kW})}{P_L(\$/\text{kW})} = \frac{N}{(1+d)\text{PVF}(d,N)} = \frac{N}{(1+d)}\left[\frac{d(1+d)^N}{(1+d)^N-1}\right]$$

$$= N\left[\frac{d(1+d)^{N-1}}{(1+d)^N-1}\right]$$

- Equation shows is the ratio of the **small-plant-to-large-plant capital costs ($/kW)** that makes them equivalent on a present worth basis

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Example 2. Present Value Benefit of Small Increments of Capacity

Q:

Find the present value advantage of eight small plants, each supplying 1 year's worth of growth, over one large plant satisfying 8 years of growth. Use a discount rate of 10%/yr. Each plant takes 1 year to build. If the large one costs $1000/kW, how much can the small ones cost to be equivalent?

Example 2. Present Value Benefit of Small Increments of Capacity

Answer:

$$\frac{P_S(\$/\text{kW})}{P_L(\$/\text{kW})} = \frac{N}{(1+d)\text{PVF}(d,N)} = \frac{N}{(1+d)}\left[\frac{d(1+d)^N}{(1+d)^N - 1}\right]$$

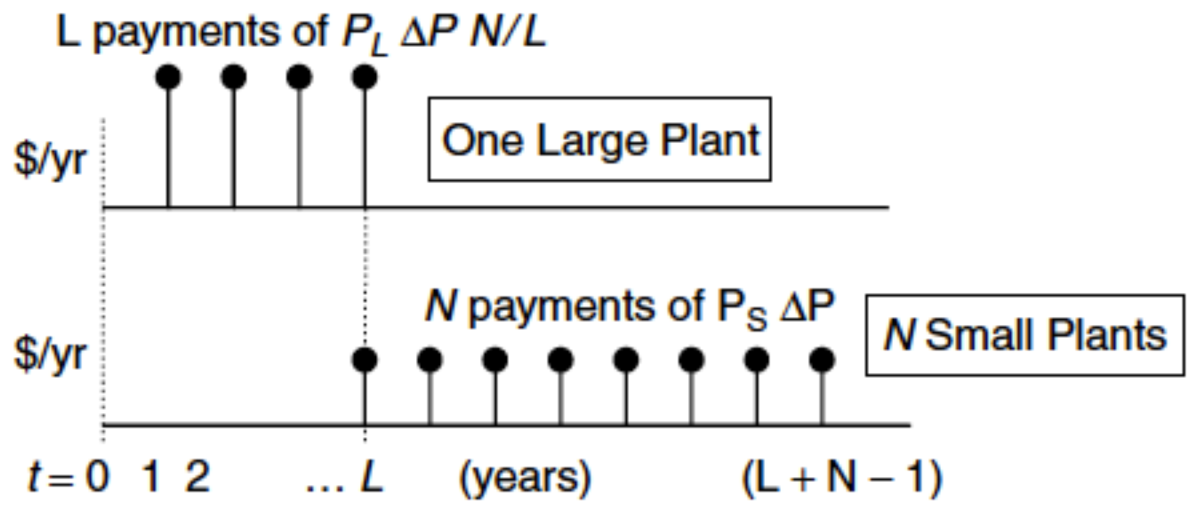
$$= N\left[\frac{d(1+d)^{N-1}}{(1+d)^N - 1}\right]$$

$$\frac{P_S(\$/\text{kW})}{P_L(\$/\text{kW})} = 8\left[\frac{0.1(1+0.1)^7}{(1+0.1)^8 - 1}\right] = 1.363$$

- This means the small DG plants can cost \$1363/kW and they still would be equivalent to the single large one at \$1000/kW

Option Values

Figure 3. The payments made on one large plant spread over the L years of lead time that it takes to bring it on line, and annual payments made on N small plants. The first of each type comes on line in year L



Option Values

Imagine the initial cost of the large plant being spread over years 1 through L, where L is the lead time. Also, suppose payments on the N small plants begin in year L, as shown in Fig. 3. We continue to assume the small plants can be built in one year.

- The present value of the payments made on the large plant costing $P_L N \Delta P$ spread out over L years is given by

$$\mathrm{PV}_L = \frac{P_L N \Delta P}{L} \cdot \mathrm{PVF}(d, L)$$

Option Values

- For the N small plants, each costing P_s ΔP over years L to L + N − 1, we have

$$PV_S = \frac{1}{(1+d)^{L-1}}[P_S \Delta P \cdot \mathrm{PVF}(d, N)]$$

- Ratio of capital costs for small and large plants, including the extra lead time for the large one

$$\frac{P_S(\$/\mathrm{kW})}{P_L(\$/\mathrm{kW})} = \frac{N(1+d)^{L-1}}{L} \cdot \frac{\mathrm{PVF}(d, L)}{\mathrm{PVF}(d, N)}$$

where ***N*** is the number of small plants, each taking 1 year to build and satisfying 1 yr of growth; ***L*** represents the years of lead time for the single large plant; and ***d*** is the discount rate.

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Example 3. Option Value of Small Plants Including Short Lead-Time Advantage

Q:

- Find the capital cost that could be paid for eight small plants, each sized to supply one year of load growth and each taking 1 year to build, compared with one large plant that supplies 8 years of growth. The large plant costs $1000/ kW and has a lead time of 4 years to build. Use a discount rate of 10%/yr

Example 3. Option Value of Small Plants Including Short Lead-Time Advantage

Answer:

$$\text{PVF}(d, L) = \frac{(1+d)^L - 1}{d(1+d)^L} = \frac{(1+0.1)^4 - 1}{0.1(1+0.1)^4} = 3.1698$$

$$\text{PVF}(d, N) = \frac{(1+0.1)^8 - 1}{0.1(1+0.1)^8} = 5.3349$$

$$\frac{P_S(\$/\text{kW})}{P_L(\$/\text{kW})} = \frac{N(1+d)^{L-1}}{L} \cdot \frac{\text{PVF}(d, L)}{\text{PVF}(d, N)} = \frac{8(1+0.1)^{4-1}}{4} \times \frac{3.1698}{5.3349} = 1.582$$

- The capital cost of the small plants can be \$1582/kW, and they would still be equivalent to one large plant costing \$1000/kW.

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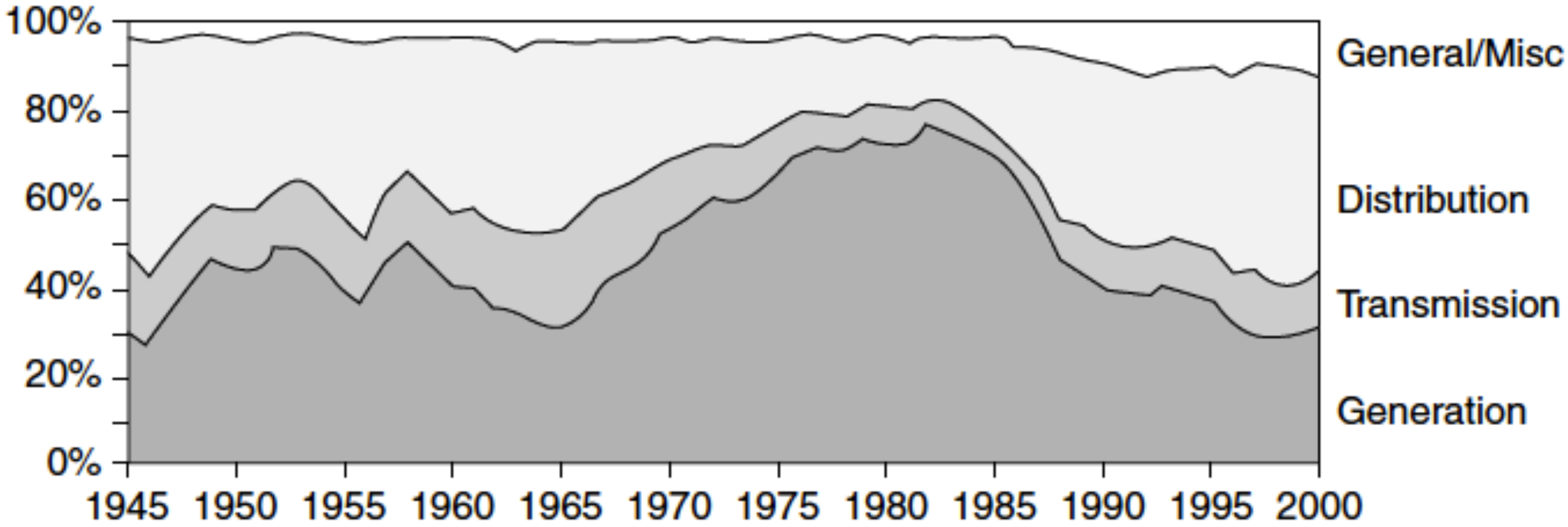
Distributed Cost Deferral

Figure 4. Allocation of U.S. investor-owned utilities' construction expenditures. **From** Lovins et al. (2002)



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Electrical Engineering Cost Benefits

When current flows through conductors

- There is voltage drop due to Ohm's law, $\Delta V = i\ R$.
- There is power loss due to i^2R heating of the wires.

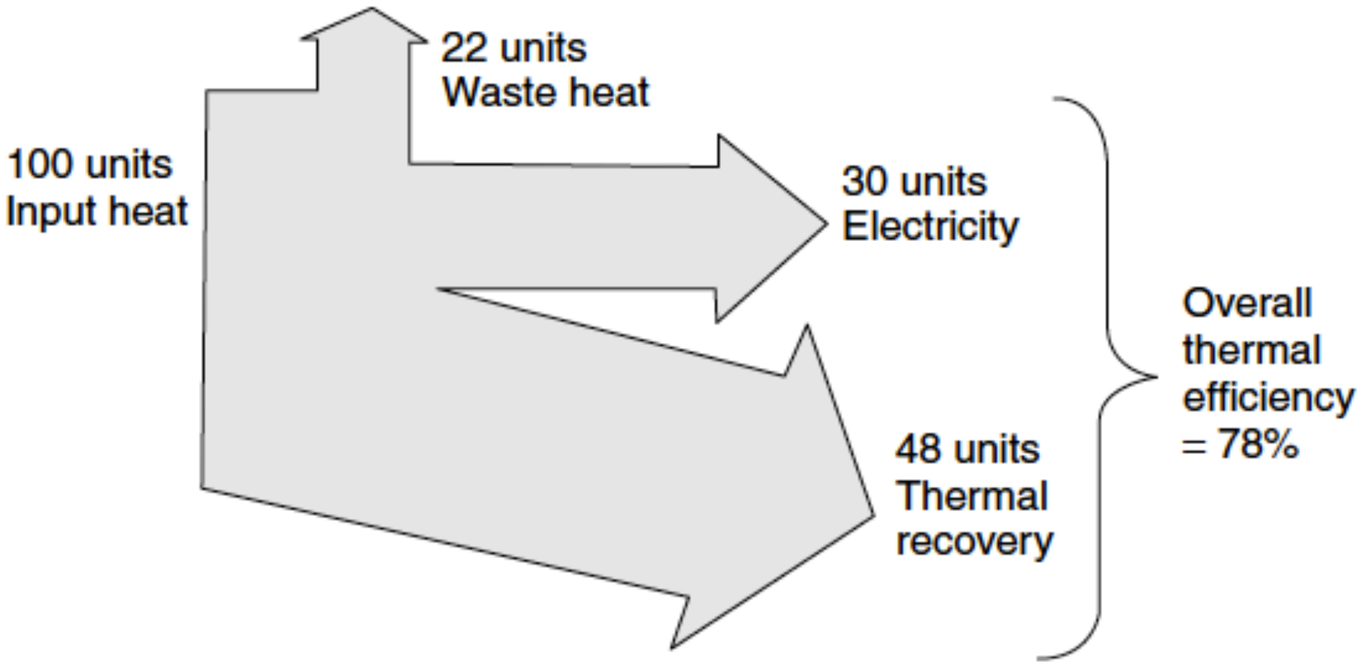
The longer the distance and the greater the current, the more there will be voltage drop and power loss in the wires

DGD 6

03/07/2013

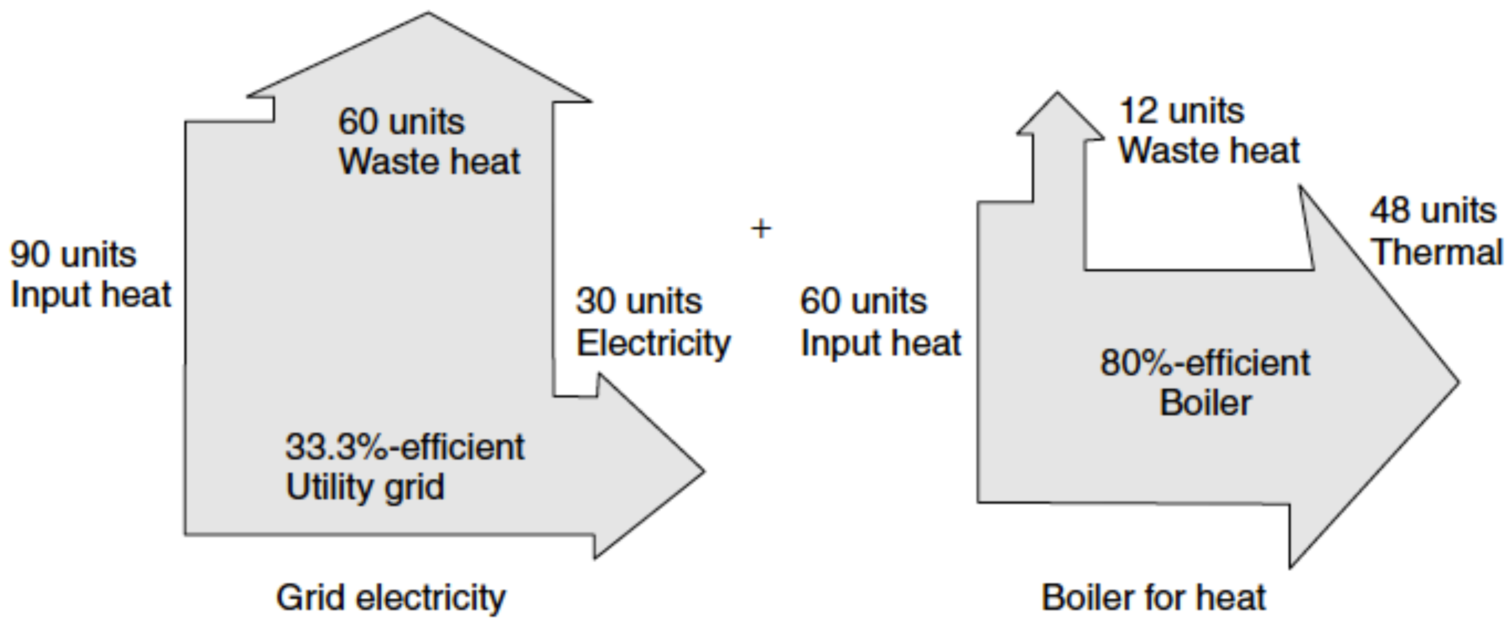
Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

- **Figure 5:** A cogeneration plant with an overall thermal efficiency of 78%



Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

- **Figure 6:** Separate generation of heat in an 80%-efficient boiler, and electricity from the grid at 33.3% efficiency, requires 150 units of thermal input compared to the 100 needed by the CHP plant of Fig. 1



Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

Compare the overall thermal efficiency with and without cogeneration

$$\text{Overall thermal efficiency (with CHP)} = \left(\frac{30 + 48}{100}\right) \times 100\%$$
$$= 78\%$$

$$\text{Overall thermal efficiency (without CHP)} = \left(\frac{30 + 48}{90 + 60}\right) \times 100\%$$
$$= 52\%$$

- By comparing the overall thermal efficiencies, the improvement caused by CHP is easy to determine. The improvement is called the **overall energy savings**

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

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

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

- where the two approaches (with and without CHP) must deliver the same electrical and thermal outputs

- For figure 5 and 6:

$$\text{Overall energy savings} = \left(1 - \frac{100}{90 + 60}\right) \times 100\% = 33.3\%$$

Energy-efficiency Measures of Combined Heat and Power (Cogeneration)

From **industrial facility** point of view:

- Under the assumption that the facility needs heat anyway, say for process steam, the **extra thermal input needed to generate electricity** using cogeneration can be described using a quantity called the **Energy-Chargeable-to-Power (ECP)**

$$\text{ECP} = \frac{\text{Total thermal input} - \text{Displaced thermal input}}{\text{Electrical output}}$$

- **Unit:** Btu/kWh or kJ/kWh

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Example 4: Cost of Electricity from a CHP Microturbine

Q:

- An industrial facility that needs a continuous supply of process heat is considering a **30 kW microturbine** to help fill that demand. Waste heat recovery will offset fuel needed by its existing 75-percent efficient boiler. The microturbine has a 29% electrical efficiency and it recovers 47% of the fuel energy as usable heat. Find the Energy-Chargeable-to-Power (ECP)

We know:

1 kW = 3412.142 Btu/hr

Example 4: Cost of Electricity from a CHP Microturbine

Anwer:

- Finding the thermal input to the 29 percent efficient, 30 kW microturbine

$$\text{Microturbine input} = \left(\frac{30\ \text{kW}}{0.29}\right) \times 3412\ \text{Btu/kWh} = 352{,}966\ \text{Btu/hr}$$

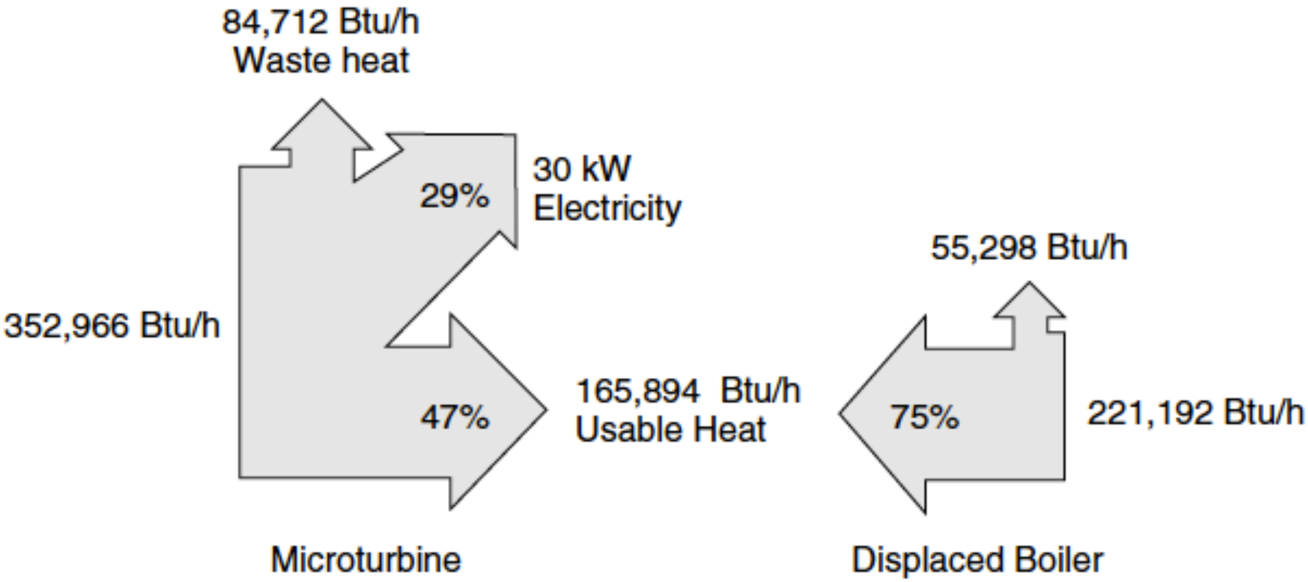
- Since 47 percent of that is delivered as usable heat

$$\text{Microturbine usable heat} = 0.47 \times 352{,}966\ \text{Btu/hr} = 165{,}894\ \text{Btu/hr}$$

- The displaced fuel for the 75 percent efficient boiler will be

$$\text{Displaced boiler fuel} = \frac{165{,}894\ \text{Btu/hr}}{0.75} = 221{,}192\ \text{Btu/hr}$$

Example 4: Cost of Electricity from a CHP Microturbine



$$\text{ECP} = \frac{\text{Extra CHP thermal input}}{\text{Electrical output}} = \frac{(352{,}966 - 221{,}192)\ \text{Btu/hr}}{30\ \text{kW}}$$

$$= 4393\ \text{Btu/kWh}$$

Example 5. Cost Chargeable to Power for a CHP Microturbine

Q:

- Suppose the 30-kW microturbine in Example 4 costs \$50,000 and has an annual O&M cost of \$1200 per year. It operates 8000 hours per year and the owner uses a fixed charge rate of 12%/yr. Natural gas for the microturbine and existing boiler costs \$4 per million Btu.

  a. Find the operating cost chargeable to power (CCP)
  b. What is the cost of electricity from the microturbine?

$$\text{Cost chargeable to power (CCP)} = \text{ECP} \times \text{Unit cost of energy}$$

Example 5. Cost Chargeable to Power for a CHP Microturbine

Answer:

a. Find the operating cost chargeable to power (CCP)

In Example 4, the energy cost chargeable to power for this microturbine was found to be 4393 Btu/kWh. The cost chargeable to power is

$$\text{Cost chargeable to power (CCP)} = \text{ECP} \times \text{Unit cost of energy}$$

$$\text{CCP} = 4393\ \text{Btu/kWh} \times \$4/10^6\ \text{Btu} = \$0.0145/\text{kWh}$$

That is, choosing to generate on-site power will cost 1.45¢/kWh for fuel.

Example 5. Cost Chargeable to Power for a CHP Microturbine

b. What is the cost of electricity from the microturbine?

The amortized cost of the microturbine:

$$\$50{,}000 * 0.12/\text{yr} = \$6{,}000/\text{yr}$$

Annual operations and maintenance = $1200/yr

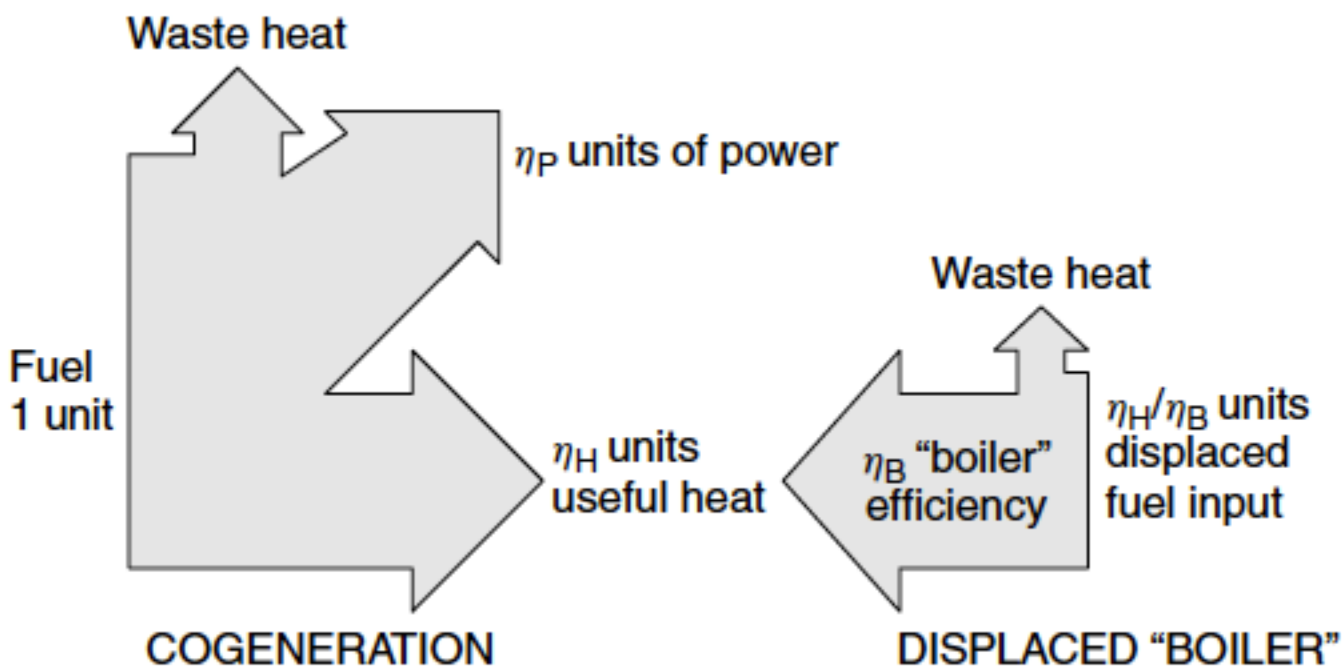
Annual fuel cost for electricity:

$$30\text{ kW} * 8000\text{ hr/yr} * \$0.0145/\text{kWh} = \$3480/\text{yr}$$

$$\text{Electricity cost} = \frac{(\$6000 + \$1200 + \$3480)/\text{yr}}{30\text{ kW} \times 8000\text{ h/yr}} = \$0.0445/\text{kWh}$$

Impact of Usable Thermal Energy on CHP Economics

- **Figure 7.** The economics of cogeneration are affected by the efficiency with which CHP fuel is converted into power and useful heat, as well as the efficiency of the boiler (or furnace or steam generator) that CHP heat displaces



Impact of Usable Thermal Energy on CHP Economics

$$\text{Electrical output (kWh)} = \frac{1\ (\text{Btu}) \times \eta_P}{3412\ (\text{Btu/kWh})}$$

$$\text{Displaced thermal input (Btu)} = \frac{1\ (\text{Btu}) \times \eta_H}{\eta_B}$$

$$\text{ECP} = \frac{\text{Total thermal input} - \text{Displaced thermal input}}{\text{Electrical output}}$$

$$= \frac{\left(1 - \frac{\eta_H}{\eta_B}\right)}{\eta_P} \times 3412\ \text{Btu/kWh}$$

$$\text{ECP} = \frac{3412}{\eta_P}\left(1 - \frac{\eta_H}{\eta_B}\right)\text{Btu/kWh} = \frac{3600}{\eta_P}\left(1 - \frac{\eta_H}{\eta_B}\right)\text{kJ/kWh}$$

Example 6. Cost of Electricity from a Fuel Cell

Q: A fuel cell with an integral reformer generates heat and electricity for an apartment house from natural gas fuel. The heat is used for domestic water heating, displacing gas needed by the apartment house boiler. The following data describe the system:

- Fuel cell rated output = 10 kW
- Capacity factor CF = 0.90
- Fuel cell/reformer electrical efficiency η_P = 0.40 (40%)
- Fuel to useful heat efficiency $\eta_H = 0.42$
- Boiler efficiency $\eta_B = 0.85$
- Capital cost of the system = \$30,000
- Paid for with an 8%, 20-year loan
- Price of natural gas \$0.80/therm (\$8/10^6 Btu)

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Example 6. Cost of Electricity from a Fuel Cell

a. Find the energy, and cost of fuel, chargeable to power?

The energy chargeable to power:

$$\mathrm{ECP} = \frac{3412}{\eta_P}\left(1 - \frac{\eta_H}{\eta_B}\right)\ \mathrm{Btu/kWh} = \frac{3412}{0.40}\left(1 - \frac{0.42}{0.85}\right) = 4315\ \mathrm{Btu/kWh}$$

The fuel cost chargeable to power:

$$\mathrm{CCP} = 4315\ \mathrm{Btu/kWh} \times \$8/10^6\ \mathrm{Btu} = \$0.0345/\mathrm{kWh}$$

Example 6. Cost of Electricity from a Fuel Cell

b. Find the cost of electricity (ignore inflation and tax benefits)?

With a 90% capacity factor, the annual electricity delivered will be

$$\text{Electricity} = 10 \text{ kW} \times 8760 \text{ h/yr} \times 0.90 = 78{,}840 \text{ kWh/yr}$$

The capital recovery factor is CRF(0.08,20)=0.1019/yr, so the annualized capital cost of the system is

$$A = P \times \text{CRF}(i, n) = \$30{,}000 \times 0.1019/\text{yr} = \$3057/\text{yr}$$

On a per kilowatt-hour basis, the annualized capital cost is

$$\text{Annualized capital cost} = \frac{\$3057/\text{yr}}{78{,}840 \text{ kWh/yr}} = \$0.0388/\text{kWh}$$

Example 6. Cost of Electricity from a Fuel Cell

b. The fuel plus capital cost of electricity is therefore

$$\text{Electricity} = 3.45¢/\text{kWh} + 3.88¢/\text{kWh} = 7.33¢/\text{kWh}$$

- This is about the same as the average U.S. price for electricity, and considerably less than the average residential price. The gas cost for the fuel cell will increase over time due to inflation, but so will the competing price of electricity, so these factors tend to cancel each other.

DGD 5

02/07/2013

Table 2. Cash-Flow Analysis

Loan principal($) =	1000.00	Energy savings (kWh/yr) =	1500
Interest =	0.06	Price at $t = 0$ (\$/kWh) =	0.10
Loan term (yrs) =	10	Savings at $t = 0$ (\$/yr)	150
CRF(i, n) per yr =	0.13587	Escalating at (%/yr) =	5
Payments (\$/yr) =	135.87		
Tax bracket =	0.305	Personal discount rate =	0.10

End of Year	Loan Payment	Interest	Delta Principal	Loan Balance	Tax Savings	Loan Cost	Electric Savings	Net Savings	PV Savings	Cum PV Savs
0	0.00	0.00	0.00	1000.00	0.00	0.00	0.00	0.00	0.00	0.00
1	135.87	60.00	75.87	924.13	18.30	117.57	157.50	39.93	36.30	36.30
2	135.87	55.45	80.42	843.71	16.91	118.96	165.38	46.42	38.36	74.66
9	135.87	14.95	120.92	128.18	4.56	131.31	232.70	101.39	43.00	369.75
10	135.87	7.69	128.18	0.00	2.35	133.52	244.33	110.81	42.72	412.48

Loan Payment (year 2): 1000×0.13587

Interest (year 2): 0.06×924.13

Delta Principal (year 2): $135.87 - 55.45$

Loan Balance (year 2): $924.13 - 80.42$

Tax Savings (year 2): 0.305×55.45

Loan Cost (year 2): $135.87 - 16.91$

Electric Savings (year 2): 1.05×157.50

Net Savings (year 2): $165.38 - 118.96$

PV Savings (year 2): $\frac{46.42}{(1.10)^2}$

Cum PV Savs (year 2): $38.36 + 36.30$

Loan paid off (Loan Balance, year 10)

PV cumulative savings (Cum PV Savs, year 10)