Université d'Ottawa | University of Ottawa

ELG4126- Sustainable Electrical Power Systems- DGD

# Economics of Distributed Resources

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DGD 03- Jan 21, 2013

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# Question of the Week

- **Sustainable Grid Development:**

How knowledge of economic, social, and environmental interests can provide sustainable processing of grid development projects?

# Paper of the Week

***"Energy, economics and environmental impacts of renewable energy systems"***

Varun, Ravi Prakash, Inder Krishnan Bhat

Renewable and Sustainable Energy Reviews 13 (2009) 2716–2721

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# *Paper: Energy, economics and environmental impacts of renewable energy systems*

*Abstract:*

- **Three indicators:**
  - Cost of electricity generation
  - Greenhouse gas emissions
  - Energy pay-back time

- **Conclusion:**
  - **Wind** and **small hydro** are the most sustainable source for the electricity generation

# *Paper: Energy, economics and environmental impacts of renewable energy systems*

*Introduction:*

- In 2005:
  - the worldwide electricity generation was 17450 TWh
    - 40% originated from coal
    - 20% from gas
    - 16% from nuclear
    - 16% from hydro
    - 7% from oil
    - only 2% from renewable sources

# *Paper: Energy, economics and environmental impacts of renewable energy systems*

*Introduction:*

- Electricity Production:
  - **Fossil fuels**
    - in their crude form, i.e. wood, coal and oil have traditionally been an extensive used energy resource.
  - **Nuclear power**
    - due to a number of reasons is not accessible to the vast majority of the world and has found its application only within developed countries
  - **Renewable energy**
    - resources are easily accessible to mankind around the world

# *Paper: Energy, economics and environmental impacts of renewable energy systems*

- Sustainability indicators of renewable energy technologies
  - Energy pay-back time
  - GHG emissions
  - Cost of electricity generation
- **Energy pay-back time:**
  - means years to recover primary energy consumption throughout its life cycle by its own energy production

$$\text{EPBT (years)} = \frac{\text{Total primary energy requirement of system throughout its life cycle (GJ)}}{\text{Annual primary energy generation by the system (GJ/year)}}$$

# *Paper: Energy, economics and environmental impacts of renewable energy systems*

- **GHG emissions:**

$$\text{GHG emissions} = \frac{\text{Total } CO_2 \text{ emissions throughout its life cycle } (gCO_{2eq})}{\text{Annual power generation } (kWh_e/\text{year}) \times \text{lifetime (year)}}$$

- **Cost of electricity generation:**
  - An average cost of production of electricity over the full life cycle of each generation technology accounting for construction, installation, operation, maintenance, decommissioning, …

$$\text{Cost of electricity generation} = \frac{\text{Annualised expenses of the system (cent/year)}}{\text{Annual eleltricity generation by the system } (kWh_e/\text{year})}$$

# *Paper: Energy, economics and environmental impacts of renewable energy systems*

Sustainability indicators for **wind energy systems**

| S. no. | Year | Location | Power rating (kW) | Life (years) | EPBT (years) | GHG emissions ($gCO_{2eq}/kWh_e$) | Cost (US cent/$kWh_e$) |
|---|---|---|---|---|---|---|---|
| 1. | 1997 [22] | Denmark | 30 | 20 | 0.39 | 16.5 | NA |
| 2. | 1996 [23] | Japan | 100 | 20 | NA | 123.7 | NA |
| 4. | 1999 [24] | India[a] | 1500 | 20 | 1.0 | 19 | NA |
| 5. | 1996 [25] | UK | 6600 | 20 | NA | 25 | NA |
| 6. | 2001 [26] | Japan | 100 | 25 | 1.4 | 39.4 | NA |
| 7. | 2005 [6] | Japan | 300 | NA | NA | 29.5 | NA |
| 8. | 2007 [27] | Turkey | 22.5 | 25 | 1.4 | 20.5 | 5-74 |

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# *Paper: Energy, economics and environmental impacts of renewable energy systems*

Sustainability indicators for **PV systems**

| S. no. | Year | Location | Type of cell | Life time (years) | Power rating (kW) | GHG emissions ($gCO_{2eq}/kWh_e$) | EPBT (years) | Cost (US cent/$kWh_e$) |
|---|---|---|---|---|---|---|---|---|
| 1. | 2006 [29] | UK | mc-si | NA | 14.4 | 44 | 8 | NA |
| 2. | 2000 [30] | India | c-si | 20 | .035 | 300 | NA | NA |
| 3. | 2000 [31] | Italy | c-si | 30 | 3300 | 60 | 3.2 | NA |
| 4. | 2000 [31] | Italy | a-si | 30 | 3300 | 50 | 2.7 | NA |
| 5. | 1997 [6] | Japan | c-si | 20 | 3 | 91 | 15.5 | NA |
| 6. | 2008 [15] | China | c-si | 30 | 100000 | 12.1 | 1.9 | 19–20 |
| 7. | 2006 [16] | Singapore | c-si | 25 | 2.7 | 165 | 4.5 | 57 |
| 8. | 2008 [15] | China | c-si | 30 | 100000 | 9.4 | 1.5 | 19–20 |
| 9. | 2008 [15] | China | a-si | 30 | 100000 | 15.6 | 2.5 | 19–20 |
| 10. | 1995 [32] | India | c-si | NA | 35 $kWh_e/m^2$ | NA | 3.95 | NA |

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# *Paper: Energy, economics and environmental impacts of renewable energy systems*

Sustainability indicators for **solar thermal systems**

| S. no. | Year of study | Location | Type | Life time (years) | Power rating (MW) | EPBT (years) | GHG emissions ($gCO_{2eq}/kWh_e$) | Cost (US cent/$kWh_e$) |
|---|---|---|---|---|---|---|---|---|
| 1. | 1999 [34] | Australia | Central receiver | NA | 100 | NA | 36.2 | NA |
| 2. | 2008 [35] | Spain | Central tower | 25 | 17 | NA | 202 | NA |
| 3. | 1990 [36] | US | Central receiver | 30 | 100 | NA | 43 | NA |
| 4. | 2008 [35] | Spain | Parabolic trough | 25 | 50 | NA | 196 | NA |

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# *Paper: Energy, economics and environmental impacts of renewable energy systems*

Sustainability indicators for **small hydro systems**

| S. no. | Year | Location | Type | Life time (years) | Power rating (kW) | GHG emissions ($gCO_{2eq}/kWh_e$) | EPBT (years) | Cost (US cent/$kWh_e$) |
|---|---|---|---|---|---|---|---|---|
| 1. | 1996 [39] | Japan | Run-of river | 30 | 10000 | 18 | NA | NA |
| 2. | 2008 [40] | India | Run-of river | 30 | 50 | 74.88 | 2.71 | NA |
| 3. | 2008 [40] | India | Run-of river | 30 | 100 | 55.42 | 1.99 | NA |
| 4. | 2008 [41] | India | Run-of river | 30 | 3000 | 35.29 | 1.28 | NA |
| 5. | 2008 [41] | India | Canal-based | 30 | 250 | 35.35 | 1.31 | NA |
| 6. | 2008 [41] | India | Canal based | 30 | 1000 | 42.98 | 1.58 | NA |
| 7. | 2008 [41] | India | Canal based | 30 | 400 | 33.87 | 1.26 | NA |
| 8. | 2008 [41] | India | Dam-toe | 30 | 2000 | 31.2 | 1.1 | NA |
| 9. | 2008 [41] | India | Dam-toe | 30 | 1000 | 62.4 | 2.25 | NA |

## *Paper: Energy, economics and environmental impacts of renewable energy systems*

**Figure of Merit**

- General meaning:
  - used to compare the different system based upon
    - their performance
    - net energy requirement
    - gross carbon emission from the systems
- In this paper:
  - to evaluate the different sustainability indicators on single platform by giving them equal

$$FM = \text{Relative rank}_{cost} \times \text{Relative rank}_{GHG\ emisions} \times \text{Relative rank}_{EPBT}$$

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# *Figure of Merit for Renewable Based Electricity Sources*

| S. no. | Year | Location | Source | Type | Life time (years) | Power rating (kW) | Cost (US cents/kWh$_e$) | | EPBT (years) | | GHG emissions ($gCO_{2eq}/kWh_e$) | | FM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Cost | Relative | EPBT | Relative | GHG | Relative | |
| 1. | 1997 | Denmark | Wind | Offshore | 20 | 30 | 7 | 9 | 0.39 | 10 | 16.5 | 10 | 900 |
| 2. | 1999 | India | Wind | NA | 20 | 1500 | 7 | 9 | 1.0 | 10 | 19 | 10 | 900 |
| 3. | 2001 | Japan | Wind | Offshore | 25 | 100 | 7 | 9 | 1.4 | 9 | 39.4 | 9 | 729 |
| 4. | 2007 | Turkey | Wind | Urban area | 25 | 22.5 | 7 | 9 | 1.4 | 9 | 20.5 | 9 | 729 |
| 5. | 2006 | UK | Solar PV | mc-si | NA | 14.4 | 24 | 3 | 8 | 2 | 44 | 8 | 48 |
| 6. | 2000 | India | Solar PV | c-si | 20 | 0.035 | 24 | 3 | 1.0 | 10 | 300 | 1 | 30 |
| 7. | 2000 | Italy | Solar PV | c-si | 30 | 3300 | 24 | 3 | 3.2 | 7 | 60 | 8 | 168 |
| 8. | 2000 | Italy | Solar PV | a-si | 30 | 3300 | 24 | 3 | 2.7 | 8 | 50 | 8 | 192 |
| 9. | 1997 | Japan | Solar PV | c-si | 20 | 3 | 24 | 3 | 15.5 | 1 | 91 | 6 | 18 |
| 10. | 2008 | China | Solar PV | c-si | 30 | 100000 | 19–20 | 4 | 1.9 | 9 | 12.1 | 10 | 360 |
| 11. | 2006 | Singapore | Solar PV | c-si | 25 | 2.7 | 57 | 1 | 4.5 | 6 | 165 | 2 | 12 |
| 12. | 2008 | China | Solar PV | c-si | 30 | 100000 | 19–20 | 4 | 1.5 | 9 | 9.4 | 10 | 360 |
| 13. | 2008 | China | Solar PV | a-si | 30 | 100000 | 19–20 | 4 | 2.5 | 8 | 15.6 | 10 | 320 |
| 14. | 1999 | Australia | Solar thermal | Central receiver | NA | 100 | 20 | 4 | 1 | 10 | 36.2 | 9 | 360 |
| 15. | 2006 | Spain | Solar thermal | Central tower | 25 | 17 | 20 | 4 | 1.02 | 9 | 202 | 1 | 36 |
| 16. | 1990 | US | Solar thermal | Central receiver | 30 | 100 | 20 | 4 | 1.04 | 9 | 43 | 8 | 288 |
| 17. | 2006 | Spain | Solar thermal | Parabolic trough | 25 | 50 | 20 | 4 | 1 | 10 | 196 | 1 | 40 |
| 18. | 2008 | India | Small hydro | Run-of river | 30 | 50 | 5 | 10 | 2.71 | 8 | 74.88 | 7 | 560 |
| 19. | 2008 | India | Small hydro | Run-of river | 30 | 100 | 5 | 10 | 1.99 | 9 | 55.42 | 8 | 720 |
| 20. | 2008 | India | Small hydro | Run-of river | 30 | 3000 | 5 | 10 | 1.28 | 9 | 35.29 | 9 | 810 |
| 21. | 2008 | India | Small hydro | Canal-based | 30 | 250 | 5 | 10 | 1.31 | 9 | 35.35 | 9 | 810 |
| 22. | 2008 | India | Small hydro | Canal based | 30 | 1000 | 5 | 10 | 1.58 | 9 | 42.98 | 8 | 720 |
| 23. | 2008 | India | Small hydro | Canal based | 30 | 400 | 5 | 10 | 1.26 | 9 | 33.87 | 9 | 810 |
| 24. | 2008 | India | Small hydro | Dam-toe | 30 | 2000 | 5 | 10 | 1.1 | 9 | 31.2 | 9 | 810 |
| 25. | 2008 | India | Small hydro | Dam-toe | 30 | 1000 | 5 | 10 | 2.25 | 8 | 62.4 | 7 | 560 |

# *Paper: Energy, economics and environmental impacts of renewable energy systems*

- Figure of merit range for different renewable electricity generation sources

| S. no. | System | Figure of merit |
|---|---|---|
| 1. | Wind | 729–900 |
| 2. | Solar PV | 12–360 |
| 3. | Solar thermal | 36–360 |
| 4. | Small hydro | 560–900 |

# REVIEW from DGD 01- Jan 7th

- Standard Residential Rates

| 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 |

- Residential Time-Of-Use (TOU) Rates

| | November–April | | May–October | |
|---|---|---|---|---|
| On-peak | 7–10 A.M., 5–8 P.M. | 8.335 ¢/kWh | 2–8 P.M. | 19.793 ¢/kWh |
| Off-peak | All other times | 7.491 ¢/kWh | All other times | 8.514 ¢/kWh |

# REVIEW from DGD 01- Jan 7th

- Demand Charges

| | Winter Oct–May | Summer June–Sept |
|---|---|---|
| Energy charges | \$0.0625/kWh | \$0.0732/kWh |
| Demand charges | \$7/mo-kW | \$9/mo-kW |

- Load Factor

$$\text{Load factor (\%)} = \frac{\text{Average power}}{\text{Peak power}} \times 100\%$$

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# REVIEW from DGD 02- Jan 14th

- Simple Payback Period

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

- Initial (Simple) Rate-Of-Return

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

- e.g. a $1000 investment which returned $500 per year would have a two year payback period and 50% rate of return per year.

# REVIEW from DGD 02- Jan 14th

- Net Present Value (NPV)

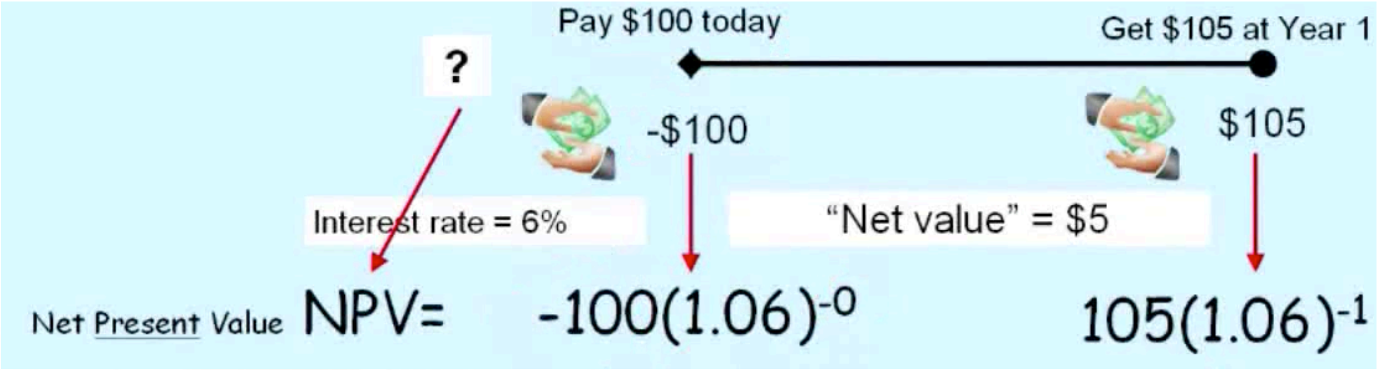
$$F = P\ (1+i)^n \qquad\qquad P = \frac{F}{(1+i)^n}$$

- e.g:


- Net Value: 5$

# REVIEW from DGD 02- Jan 14th

- Net Present Value (NPV)




- Assume Bank: interest rate: %6
  - Present value formula at year 1: $\$105(1.06)^{-1}$
  - Present value formula at year 0: $\$100(1.06)^{-0}$

$$NPV= -\$100(1.06)^{-0} + \$105(1.06)^{-1} = -\$0.94$$

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# REVIEW from DGD 02- Jan 14th

- Internal Rate of Return (IRR)
- e.g.: rate of return 3%


rate of return?!!?!


$-100(1+r)^{-0}+60(1+r)^{-1}+60(1+r)^{-2}$

IRR: 13%

# REVIEW from DGD 02- Jan 14th

- IRR: $\text{NPV} = \Delta A * \text{PVF}(\text{IRR}, n) - \Delta P = 0$

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

| 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 |

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

# DGD 03- Jan 21- Outline

- Energy Economics
  - **NPV and IRR with Fuel Escalation**
  - Annualizing the Investment
  - Levelized Bus-Bar Codes

# NPV and IRR with Fuel Escalation

- The cost of fuel is not constant and may be higher in future than what it is today
- It is worth to include a fuel price escalation factor in the present worth analysis
- We had: $$\mathrm{PVF}(d,n) = \frac{1}{1+d} + \frac{1}{(1+d)^2} + \cdots + \frac{1}{(1+d)^n}$$
- Rewrite the above equation so that it is the sum of present values for an annual amount that is worth \$1 at time t = 0, but becomes \$(1 + e ) at t = 1 year, and escalates to \$(1 + e )$^n$ in the *n*th year

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

# NPV and IRR with Fuel Escalation

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

- *d* is the buyer's discount rate and e is the escalation rate of the annual savings

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

- Therefore Equivalent discount rate with fuel escalation:

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

# Finding The IRR When There is Fuel Escalation

- New Formulas are:

$$\text{NPV} = \Delta A \times \text{PVF}(d', n) - \Delta P \quad = 0$$

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

- Where ΔA is the annual savings at *t=0*.
- $\text{IRR}_0$: Internal Rate of Return without Fuel Escalation
- $\text{IRR}_e$: Internal Rate of Return with Fuel Escalation

$$\text{IRR}_0 = \frac{d - e}{1 + e} \qquad \text{IRR}_e = \text{IRR}_0(1 + e) + e$$

# Example 1. Net Present Value of Premium Motor with Fuel Escalation

- Q: The premium motor costs an extra \$500 and saves \$192/yr at today's price of electricity. If electricity rises at an annual rate of 5%, find the net present value of the premium motor if the best alternative investment earns 10%. (for 20 years)
- *Answer:*

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

  – 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 is

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

$$\mathrm{NPV} = \$192/\mathrm{yr} * 12.717 \text{ yr} - \$500 = \$1942$$

# Example 2. IRR for an HVAC Retrofit Project with Fuel Escalation

- Q: Suppose the energy-efficiency retrofit of a large building
  - Reduces the annual electricity demand for heating and cooling from $2.3*10^6$kWh to $0.8*10^6$kWh and the peak demand for power by 150 kW
  - Electricity costs $0.06/kWh
  - Demand charges are $7/kW-mo
  - Both of which are projected to rise at an annual rate of 5%.

If the project costs $500,000, what is the internal rate of return over a project lifetime of 15 years?

# Example 2. IRR for an HVAC Retrofit Project with Fuel Escalation

- *Answer:* The initial annual savings will be
  - Energy Savings: $(2.3 - 0.8) * 10^6$ kWh/yr*$0.06/kWh = $90,000/yr
  - Demand Savings: 150 kW * $7/kW-mo * 12 mo/yr = $12,600/yr
  - Total Annual Savings: $\Delta A$ = $90,000 + $12,600 = $102,600/yr
- The Simple payback period will be

$$\text{Simple payback period} = \frac{\Delta P}{\Delta A} = \frac{\$500{,}000}{\$102{,}600/\text{yr}} = 4.87 \text{ yr}$$

- From Table 1, the internal rate of return without fuel escalation $IRR_0$ is very close to 19%.
- The internal rate of return with fuel escalation is

$$IRR_e = IRR_0(1 + e) + e = 0.19\,(1 + 0.05) + 0.05 = 0.2495 = 25\%/\text{yr}$$

# Table 1. Present Value Function to Help Estimate the Internal Rate of Return [a]

| 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 |

[a] Enter the row corresponding to project life, and move across until values close to the simple payback period, $\Delta P/\Delta A$, 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%.

# Outline

- Energy Economics
  - NPV and IRR with Fuel Escalation
  - **Annualizing the Investment**
  - Levelized Bus-Bar Codes

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# Annualizing the Investment

- Where extra capital required for an energy investment
  - will be borrowed from a lending company
  - obtained from investors who require a return on their investments
  - or taken from one's own accounts

- In all of these circumstances, the economic analysis can be thought of as a **LOAN**

  That converts the extra capital cost into a series of equal annual payments that eventually pay off the loan with interest.

# Annualizing the Investment

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

- A represents annual loan payments ($/yr)
- P is the principal borrowed ($)
- $i$ is the interest rate (e.g. 10% corresponds to $i = 0.10$/yr)
- $n$ is the loan term (yrs), and

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

- CRF is just the inverse of the present value function (PVF).
  - we are treating the first cost of the investment as a loan, we have gone back to using an interest rate *i* rather than a discount rate *d*.

# Table 2. Capital Recovery Factors as a Function of Interest Rate and 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 |

- To find the monthly payment:

$$\mathrm{CRF}(i,n) = \frac{(i/12)[1+(i/12)]^{12n}}{[1+(i/12)]^{12n}-1} \text{ per month}$$

# Example 3. Comparing Annual Costs to Annual Savings

- Q: 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.
  a. Find the annual monetary savings.
  b. Find the ratio of annual benefits to annual costs.
- *Answer:*
- The capital recovery factor:

$$\mathrm{CRF}(0.07, 10) = \frac{0.07(1+0.07)^{10}}{(1+0.07)^{10}-1} = 0.14238/\mathrm{yr}$$

- The annual payments will be A = \$1000 * 0. 14238/yr = \$142. 38/yr.

# Example 3. Comparing Annual Costs to Annual Savings

a. The annual savings will be \$200 − \$142. 38 = \$57. 62/ yr.
   - Notice that by annualizing the costs the buyer makes money every year so the notion that a 5-year payback period might be considered unattractive becomes irrelevant.

b. The benefit/cost ratio would be

$$\text{Benefit/Cost} = \frac{\$200/\text{yr}}{\$142.38/\text{yr}} = 1.4$$

# Example 4. Cost of Electricity from a Photovoltaic System

- Q: 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).

- *Answer:*
  - From Table 1, the capital recovery factor is 0.0872/yr
  - The annual payment:

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

# Example 4. Cost of Electricity from a Photovoltaic System

- *Answer:*
  - The annual electricity generated:

(8760 = 365 * 24)

Annual Energy (kWh/yr) = Rated Power (kW) * 8760 hr/yr * CF

Annual energy = 3kW * 8760 h/yr * 0.25 = 6570 kWh/yr

  - The cost of electricity from the PV system is therefore

$$\text{Cost of PV electricity} = \frac{\$872/\text{yr}}{6570\ \text{kWh/yr}} = \$0.133/\text{kWh} = 13.3¢/\text{kWh}$$

# Outline

- Energy Economics
  - NPV and IRR with Fuel Escalation
  - Annualizing the Investment
  - **Levelized Bus-Bar Codes**

# Levelized Bus-Bar Codes

- To do an adequate **comparison** of **cost per kilowatt-hour** from a renewable energy system versus that for a fossil-fuel-fired power plant, **the potential for escalating future fuel costs** must be accounted for.
- key advantages of the renewable energy systems
  - independence from the uncertainties associated with future fuel costs.
- The cost of electricity per kilowatt-hour for a power plant has two key components
  - an up-front fixed cost to build the plant
  - an assortment of costs that will be incurred in the future

# Levelized Bus-Bar Codes

- The usual approach to cost estimation:
  - Finding an **equivalent initial cost**: A present value calculation
  - **Spreading out the amount into a uniform series of annual costs**.
- **The ratio of the equivalent annual cost ($/yr) to the annual electricity generated (kWh/year) is called the *Levelized Bus-Bar* Cost of power**
- *the "bus-bar" refers to the wires as they leave the plant boundaries*
- In the first step, the present value of all future costs must be found, including the impacts of inflation. To keep things simple, we'll assume that the annual costs today are $A_0$, and that they escalate due to inflation (and other factors) at the rate *e*. Figure 1 illustrates the concept.

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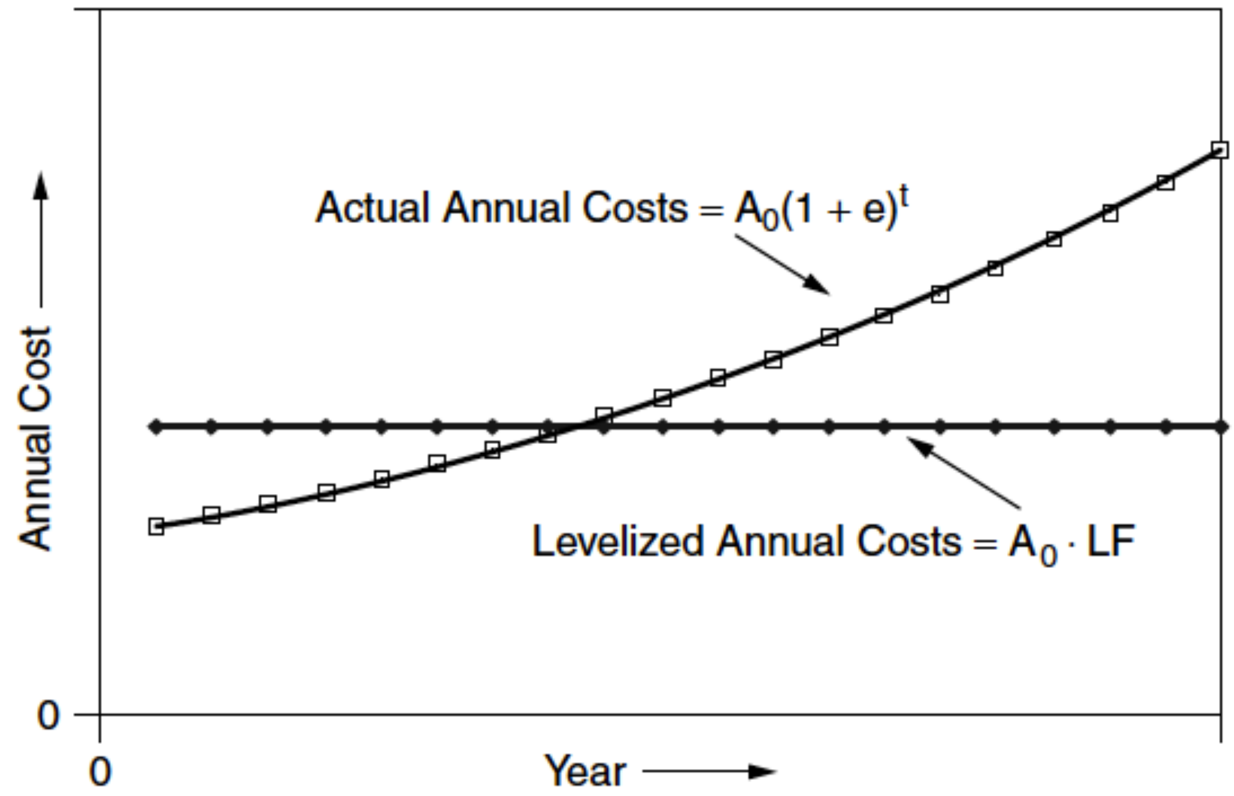
# Figure 1. Levelizing annual costs when there is fuel escalation

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# Levelized Bus-Bar Codes

- The present value of the escalating annual costs over a period of n years is given by

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

where $d'$ is the equivalent discount rate including inflation introduced in

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

Having found the present value of those future costs, we now want to find an equivalent annual cost using the capital recovery factor

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

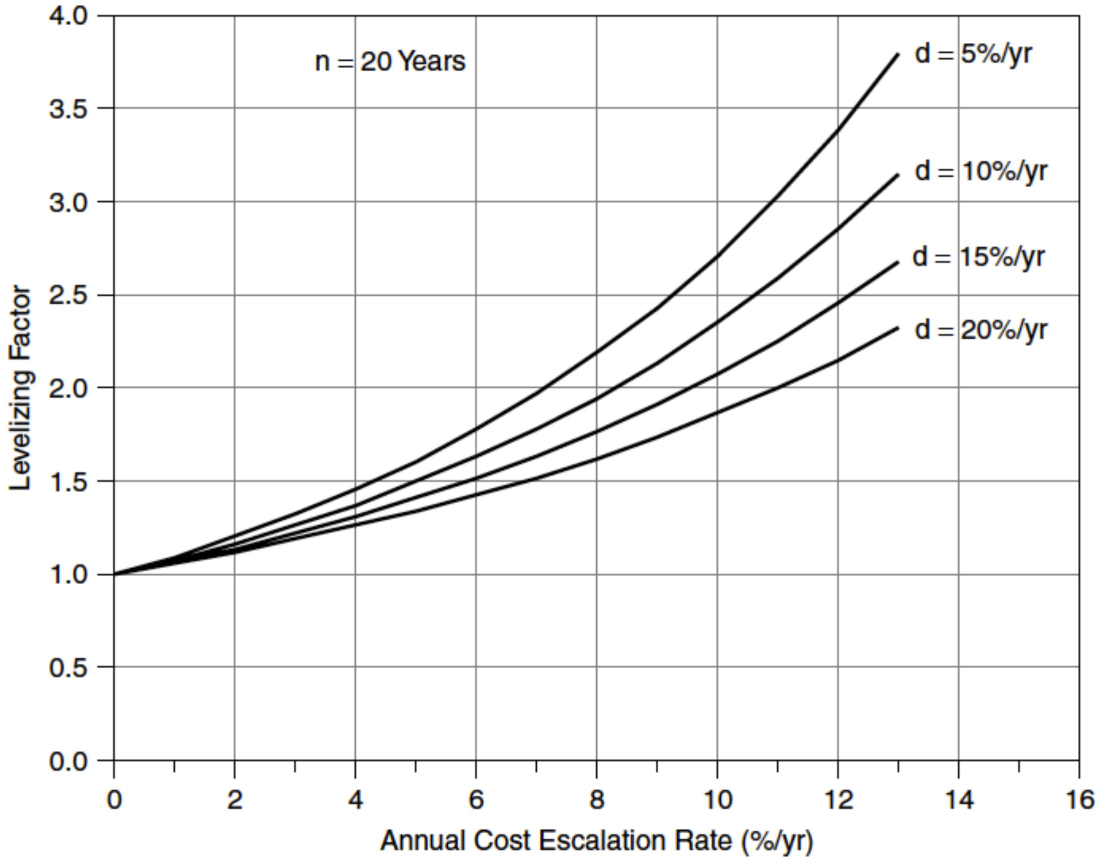
# Levelized Bus-Bar Codes

- The product in the brackets, called the levelizing factor , is a multiplier that converts the escalating annual fuel and O&M costs into a series of equal annual amounts:

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

- Notice that when there is no escalation ($e$ =0), the $d'$=$d$ and the levelizing factor is just unity!
- The impact of the levelizing factor can be very high, as is illustrated in Figure 2.

# Figure 2. Levelizing Factor

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# Figure 2. Levelizing Factor

- Levelizing Factor for a 20-year term as a function of the escalation rate of annual costs, with the owner's discount rate as a parameter.
- e.g. if fuel prices increase at 5%/yr for an owner with a 10% discount rate, the levelizing factor is 1.5. If they increase at 8.3%/yr, the impact is equivalent to an annualized cost of fuel that is double the initial cost.
- Normalizing the levelized annual costs to a per kWh basis by using:
  - the heat rate of the plant (Btu/kWh)
  - the initial fuel cost ($/Btu)
  - the per kWh O&M costs
  - the levelizing factor

# Levelized Bus-Bar Codes

- Levelized annual costs:

$$\text{Levelized annual costs}(\$/\text{kWh}) = \left[\text{Heat rate}\left(\frac{\text{Btu}}{\text{kWh}}\right) \times \text{Fuel}\left(\frac{\$}{\text{Btu}}\right) + \text{O \& M}\left(\frac{\$}{\text{kWh}}\right)\right]_0 \times \text{LF}$$

# Levelized Bus-Bar Codes

- Just as the future cost of fuel and O&M needs to be levelized, so does the capital cost of the plant.
- To do so
  - Combine the CRF with other costs that depend on the capital cost of the plant into a quantity called the ***fixed charge rate (FCR)***
- The fixed charge rate covers costs that are incurred even if the plant doesn't operate, including depreciation, return on investment, insurance, and taxes.
- Fixed charge rates vary depending on plant ownership and current costs of capital, but tend to be in the range of 10–18% per year.

# Levelized Bus-Bar Codes

- The governing equation that annualizes capital costs is then

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

- Where CF is the capacity factor of the plant
- Table 2 provides estimates for some of the key variables in last two equations.

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# Table 3. Example Cost Parameters for Power Plants

| Technology | Fuel | Capital Cost ($/kW) | Heat Rate (Btu/kWh) | Fuel Cost ($/million Btu) | Variable O&M (¢/kWh) |
|---|---|---|---|---|---|
| Pulverized coal steam | Coal | 1400 | 9,700 | 1.50 | 0.43 |
| Advanced coal steam | Coal | 1600 | 8,800 | 1.50 | 0.43 |
| Oil/gas steam | Oil/Gas | 900 | 9,500 | 4.60 | 0.52 |
| Combined cycle | Natural gas | 600 | 7,700 | 4.50 | 0.37 |
| Combustion turbine | Natural gas | 400 | 11,400 | 4.50 | 0.62 |
| STIG gas turbine | Natural gas | 600 | 9,100 | 4.50 | 0.50 |
| New hydroelectric | Water | 1900 | — | 0.00 | 0.30 |

*Source*: Based on data from Petchers (2002) and UCS (1992).

# Example 5. Cost of Electricity from a Micro-turbine

- Q: A micro-turbine has the following characteristics:
  - Plant cost = $850/kW
  - Heat rate = 12,500 Btu/kWh
  - Capacity factor = 0.70
  - Initial fuel cost = $4.00/$10^6$ Btu
  - Variable O&M cost = $0.002/kWh
  - Fixed charge rate = 0.12/yr
  - Owner discount rate = 0.10/yr
  - Annual cost escalation rate = 0.06/yr

Find its levelized ($/kWh) cost of electricity over a 20-year lifetime

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# Example 5. Cost of Electricity from a Micro-turbine

- *Answer:*
  - We know:

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

  - Therefore:

$$\text{Levelized fixed cost} = \frac{\$850/\text{kW} \times 0.12/\text{yr}}{8760\ \text{h/yr} \times 0.70} = \$0.0166/\text{kWh}$$

  - We know: (Levelized annual costs = $A_0$* LF

$$\text{Levelized annual costs}(\$/\text{kWh}) = \left[\text{Heat rate}\left(\frac{\text{Btu}}{\text{kWh}}\right) \times \text{Fuel}\left(\frac{\$}{\text{Btu}}\right) + \text{O \& M}\left(\frac{\$}{\text{kWh}}\right)\right]_0 \times \text{LF}$$

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# Example 5. Cost of Electricity from a Micro-turbine

– Therefore the initial annual cost for fuel and O&M is

$A_0$=12,500 Btu/kWh * \$400/$10^6$ Btu + \$0.002/kWh = \$0.052/kWh

This needs to be levelized to account for inflation.

– We know:

$$\text{Equivalent discount rate with fuel escalation} = d' = \frac{d-e}{1+e}$$

– Therefore the inflation adjusted discount rate d would be

$$d' = \frac{d-e}{1+e} = \frac{0.10-0.06}{1+0.06} = 0.037736$$

# Example 5. Cost of Electricity from a Micro-turbine

– We know:

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

– Therefore we have:

$$\text{Levelizing factor (LF)} = \left[\frac{(1.037736)^{20} - 1}{0.037736(1.037736)^{20}}\right] \cdot \left[\frac{0.10(1.10)^{20}}{(1.10)^{20} - 1}\right] = 1.628$$

– Levelized annual cost:

$A_0LF$ = \$0.052/kWh * 1.628 = \$0.0847

– Levelized fixed plus annual cost:

– Levelized bus-bar cost = \$0.0166/kWh + \$0.0847/kWh = \$0.1013/kWh