SOLUTIONS MANUAL FOR

# PRINCIPLES OF SOLAR ENGINEERING

Third Edition

by

Philip D. Myers, Jr.
Gunnar O. Tamm
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# Chapter 1
# Introduction to Solar Energy Conversion

**1.1**

The yearly capacity and fractions are tabulated below.

| *Year* | *Renewable (total)* | *Solar* | *Biomass* | *Wind* | *Hydroelectic* | *Total capacity* | *Non-renewable* |
|---|---|---|---|---|---|---|---|
| 2011 | 20.1 | 0.2814 | 1.809 | 2.01 | 15.9996 | 100 | 79.9 |
| 2012 | 21.2803 | 0.4221 | 2.02608 | 2.5125 | 16.3196 | 102.4 | 81.1197 |
| 2013 | 22.689 | 0.63315 | 2.26921 | 3.14063 | 16.646 | 104.858 | 82.1686 |
| 2014 | 24.3959 | 0.94973 | 2.54151 | 3.92578 | 16.9789 | 107.374 | 82.9783 |
| 2015 | 26.4968 | 1.42459 | 2.8465 | 4.90723 | 17.3185 | 109.951 | 83.4544 |
| 2016 | 29.1238 | 2.13688 | 3.18808 | 6.13403 | 17.6649 | 112.59 | 83.4661 |
| 2017 | 32.4617 | 3.20532 | 3.57065 | 7.66754 | 18.0181 | 115.292 | 82.8305 |
| 2018 | 36.77 | 4.80798 | 3.99912 | 9.58443 | 18.3785 | 118.059 | 81.2891 |
| 2019 | 42.4176 | 7.21197 | 4.47902 | 11.9805 | 18.7461 | 120.893 | 78.475 |
| 2020 | 49.9311 | 10.818 | 5.0165 | 14.9757 | 19.121 | 123.794 | 73.8629 |
| 2021 | 60.0684 | 16.2269 | 5.61848 | 18.7196 | 19.5034 | 126.765 | 66.6966 |
| 2022 | 73.9261 | 24.3404 | 6.2927 | 23.3995 | 19.8935 | 129.807 | 55.8813 |
| 2023 | 93.0992 | 36.5106 | 7.04782 | 29.2493 | 20.2914 | 132.923 | 39.8236 |
| 2024 | 119.918 | 54.7659 | 7.89356 | 36.5617 | 20.6972 | 136.113 | 16.1946 |
| 2025 | 157.803 | 82.1489 | 8.84079 | 45.7021 | 21.1111 | 139.38 | -18.423 |

It can be seen that renewables account for the entire electrical power capacity as of YR2025. The relative fractions of each renewable technology are as follows.

| | |
|---|---|
| Solar | 0.59 |
| Biomass | 0.06 |
| Wind | 0.33 |
| Hydroelectric | 0.15 |

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**1.2**

Performing an analysis similar to that of Problem 1.1, we arrive at the following values:

**a.** Renewables 1.00
**b.** Solar 0.54

---

**1.3**

For example, the fractions for YR2015 are given below.

| | |
|---|---|
| Solar | 0.01296 |
| Wind | 0.04463 |
| Biomass | 0.02311 |
| Hydroelectric | 0.15751 |

Actual data for the year in question can be obtained from a variety of sources (e.g., eia.gov). Reasons for deviations may include the assumption of constant escalation rates in both renewable capacity and total capacity. The escalation rate for solar in particular (50%) is likely too high in the long-term. Rapid growth may occur early on, but it should taper off at some point.

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**1.4**

Assume the system is purchased in YR0, tax credit received in YR1. The cash flows and cumulative present value are tabulated below.

| *Year* | *Principal* | *Tax credit* | *Savings* | *CF* | *CF(present value)* | *Cumulative PV* |
|---|---|---|---|---|---|---|
| 0 | 4000 | | | -4000 | -4000 | -4000 |
| 1 | | 1200 | 450 | 1650 | 1571.43 | -2428.6 |
| 2 | | | 450 | 450 | 408.163 | -2020.4 |
| 3 | | | 450 | 450 | 388.727 | -1631.7 |
| 4 | | | 450 | 450 | 370.216 | -1261.5 |
| 5 | | | 450 | 450 | 352.587 | -908.88 |
| 6 | | | 450 | 450 | 335.797 | -573.08 |
| 7 | | | 450 | 450 | 319.807 | -253.27 |
| 8 | | | 450 | 450 | 304.578 | 51.3029 |

Therefore, the payback period is approximately 8 years.

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**1.5**

Assume a discount rate of 5% for present worth calculations. The yearly cash flows for this system are tabulated below.

| Year | Capital cost | O&M | Total costs (present value) | Electrical output (MWhe) | Output (MWhe, discounted) | Revenue | CF(present value) |
|---|---|---|---|---|---|---|---|
| 0 | 37.5 | | 37.5 | | | | -37.5 |
| 1 | 6.20834 | 0.15 | 6.05556 | 106575 | 101500 | 15.9863 | 9.1694381 |
| 2 | 6.20834 | 0.15 | 5.7672 | 106575 | 96666.7 | 16.7856 | 9.4577982 |
| 3 | 6.20834 | 0.15 | 5.49257 | 106575 | 92063.5 | 17.6248 | 9.7324268 |
| 4 | 6.20834 | 0.15 | 5.23102 | 106575 | 87679.5 | 18.5061 | 9.9939779 |
| 5 | 6.20834 | 0.15 | 4.98193 | 106575 | 83504.3 | 19.4314 | 10.243074 |
| 6 | 6.20834 | 0.15 | 4.74469 | 106575 | 79527.9 | 20.403 | 10.480309 |
| 7 | 6.20834 | 0.15 | 4.51875 | 106575 | 75740.9 | 21.4231 | 10.706246 |
| 8 | 6.20834 | 0.15 | 4.30357 | 106575 | 72134.2 | 22.4943 | 10.921425 |
| 9 | 6.20834 | 0.15 | 4.09864 | 106575 | 68699.2 | 23.619 | 11.126357 |
| 10 | 6.20834 | 0.15 | 3.90347 | 106575 | 65427.8 | 24.7999 | 11.321531 |
| 11 | 6.20834 | 0.15 | 3.71759 | 106575 | 62312.2 | 26.0399 | 11.50741 |
| 12 | 6.20834 | 0.15 | 3.54056 | 106575 | 59344.9 | 27.3419 | 11.684438 |
| 13 | 6.20834 | 0.15 | 3.37196 | 106575 | 56519 | 28.709 | 11.853037 |
| 14 | 6.20834 | 0.15 | 3.21139 | 106575 | 53827.6 | 30.1445 | 12.013606 |
| 15 | 6.20834 | 0.15 | 3.05847 | 106575 | 51264.4 | 31.6517 | 12.16653 |
| 16 | 6.20834 | 0.15 | 2.91283 | 106575 | 48823.2 | 33.2343 | 12.312171 |
| 17 | 6.20834 | 0.15 | 2.77412 | 106575 | 46498.3 | 34.896 | 12.450877 |
| 18 | 6.20834 | 0.15 | 2.64202 | 106575 | 44284.1 | 36.6408 | 12.582978 |
| 19 | 6.20834 | 0.15 | 2.51621 | 106575 | 42175.3 | 38.4728 | 12.708789 |
| 20 | 6.20834 | 0.15 | 2.39639 | 106575 | 40167 | 40.3965 | 12.828609 |
| 21 | 6.20834 | 0.15 | 2.28228 | 106575 | 38254.3 | 42.4163 | 12.942722 |
| 22 | 6.20834 | 0.15 | 2.1736 | 106575 | 36432.7 | 44.5371 | 13.051402 |
| 23 | 6.20834 | 0.15 | 2.07009 | 106575 | 34697.8 | 46.7639 | 13.154907 |
| 24 | 6.20834 | 0.15 | 1.97152 | 106575 | 33045.5 | 49.1021 | 13.253483 |
| 25 | 6.20834 | 0.15 | 1.87764 | 106575 | 31471.9 | 51.5573 | 13.347365 |

**IRR 27%**

**LCOE, $/kWhe 0.085**

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**1.6**

New plant life is 20 years; assume a discount rate of 5% for PW calculations.

| Year | Capital cost | O&M | Salvage | Total costs (present v | Electrical output (MW | Output (MWhe, disco | Revenue | CF(present value) |
|---|---|---|---|---|---|---|---|---|
| 0 | 37.5 | | | 37.5 | | | | -37.5 |
| 1 | 7.02123 | 0.15 | | 6.82974 | 106575 | 101500 | 26.6438 | 18.545261 |
| 2 | 7.02123 | 0.15 | | 6.50451 | 106575 | 96666.7 | 26.6438 | 17.662153 |
| 3 | 7.02123 | 0.15 | | 6.19477 | 106575 | 92063.5 | 26.6438 | 16.821098 |
| 4 | 7.02123 | 0.15 | | 5.89979 | 106575 | 87679.5 | 26.6438 | 16.020093 |
| 5 | 7.02123 | 0.15 | | 5.61884 | 106575 | 83504.3 | 26.6438 | 15.257232 |
| 6 | 7.02123 | 0.15 | | 5.35128 | 106575 | 79527.9 | 26.6438 | 14.530697 |
| 7 | 7.02123 | 0.15 | | 5.09646 | 106575 | 75740.9 | 26.6438 | 13.838759 |
| 8 | 7.02123 | 0.15 | | 4.85377 | 106575 | 72134.2 | 26.6438 | 13.17977 |
| 9 | 7.02123 | 0.15 | | 4.62264 | 106575 | 68699.2 | 26.6438 | 12.552162 |
| 10 | 7.02123 | 0.15 | | 4.40251 | 106575 | 65427.8 | 26.6438 | 11.95444 |
| 11 | 7.02123 | 0.15 | | 4.19287 | 106575 | 62312.2 | 26.6438 | 11.385181 |
| 12 | 7.02123 | 0.15 | | 3.99321 | 106575 | 59344.9 | 26.6438 | 10.84303 |
| 13 | 7.02123 | 0.15 | | 3.80305 | 106575 | 56519 | 26.6438 | 10.326695 |
| 14 | 7.02123 | 0.15 | | 3.62196 | 106575 | 53827.6 | 26.6438 | 9.8349476 |
| 15 | 7.02123 | 0.15 | | 3.44948 | 106575 | 51264.4 | 26.6438 | 9.3666168 |
| 16 | 7.02123 | 0.15 | | 3.28522 | 106575 | 48823.2 | 26.6438 | 8.9205874 |
| 17 | 7.02123 | 0.15 | | 3.12878 | 106575 | 46498.3 | 26.6438 | 8.4957976 |
| 18 | 7.02123 | 0.15 | | 2.97979 | 106575 | 44284.1 | 26.6438 | 8.0912358 |
| 19 | 7.02123 | 0.15 | | 2.8379 | 106575 | 42175.3 | 26.6438 | 7.7059388 |
| 20 | 7.02123 | 0.15 | 50 | -16.142 | 106575 | 40167 | 26.6438 | 26.183464 |

For $50M salvage:

**IRR 45%**

**LCOE, $/kWhe 0.081**

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# Chapter 2
# Fundamentals of Solar Radiation

**2.1**

**a.**

Begin with Equation (2.3), neglecting refractive effects.

$$E_{b\lambda} = \frac{C_1}{\left(e^{\frac{C_2}{\lambda T}} - 1\right)\lambda^5}$$

Take $E_{b\lambda} d\lambda$ (with $\tilde{\nu} = 1/\lambda$). Hence:

$$E_{b\lambda} d\lambda = \frac{C_1 \tilde{\nu}^5 d\lambda}{\left(e^{\frac{C_2 \tilde{\nu}}{T}} - 1\right)} = -\frac{C_1 \tilde{\nu}^3 d\tilde{\nu}}{\left(e^{\frac{C_2 \tilde{\nu}}{T}} - 1\right)} = -E_{b\tilde{\nu}} d\tilde{\nu}$$

$$\therefore\ E_{b\tilde{\nu}} = \frac{C_1 \tilde{\nu}^3}{\left(e^{\frac{C_2 \tilde{\nu}}{T}} - 1\right)}$$

**b.**

Differentiate the expression from part (a) with respect to wave number. Then, set the expression equal to zero. The resulting equation is:

$$3(e^{\frac{C_2 \tilde{\nu}}{T}} - 1) = \frac{C_2 e^{\frac{C_2 \tilde{\nu}}{T}} \tilde{\nu}}{T}$$

This equation is transcendental in $\tilde{\nu}/T$. Solving numerically, we have:

$$\frac{\tilde{\nu}}{T} = 1.96\ \text{cm}^{-1}/\text{K}$$

---

**2.2**

From the problem statement, $L = 40.77°$, solar time is 2:00PM, on October 1st (n = 274). The declination angle, $\delta_s$, is obtained from Equation (2.23).

$$\delta_s = 23.45° \sin\left[\frac{360(284+n)°}{365}\right]$$
$$= -4.22°\ (-0.0736\ \text{rad})$$

To calculate the altitude angle, we need the hour angle, obtained from Equation (2.25).

$$h_s = \frac{15°}{\text{hr}}(\text{hours from solar noon}) = 30°$$

The altitude angle is obtained from Equation (2.28).

$$\sin\alpha = \sin L \sin\delta_s + \cos L \cos\delta_s \cos h_s$$
$$\alpha = 37.3°\ (0.651\ \text{rad})$$

And the zenith angle immediately follows, according to Equation (2.24).

$$z = 90° - \alpha = 52.7°\ (0.920\ \text{rad})$$

For this time / location, the sun will be south of the east-west line, so $|a_s| \leq 90°$. Hence, the azimuth angle follows directly from Equation (2.29).

$$\sin a_s = \frac{\cos\delta_s \sin h_s}{\cos\alpha}$$
$$a_s = 38.8°\ (0.678\ \text{rad})$$

---

**2.3**

**(1)** First, find the minimum normalized distance, $d$, for placement of the second collector. At solar noon, the profile angle is equal to the solar altitude angle, $\alpha_1$. From the geometry, we have the following relationships.

$$\tan\alpha_1 = \frac{h}{d}$$
$$\sin\beta = \frac{h}{w}$$

Here, $h$ is the vertical height of the collector, and $w$ is the arbitrary width. The normalized distance, $d/w$, is desired.

$$\frac{d}{w} = \frac{\sin\beta}{\tan\alpha_1}$$

The collector tilt angle, $\beta$, is known. The altitude angle follows from Equation (2.28). For Tampa, Florida, we have $L = 27.96°$N (Tampa International Airport); for December 21st, $\delta_s = -23.45°$.

$$\sin\alpha_1 = \sin L \sin\delta_s + \cos L \cos\delta_s \cos h_s$$
$$\alpha_1 = 38.6°\ (0.673\ \text{rad})$$

Normalized distance:

$$\frac{d}{w} = \frac{\sin\beta}{\tan\alpha_1}$$
$$= 0.627\ (\text{meter separation per meter width})$$

**(2)** Second, the percent shading at 9:00AM solar time is desired; this quantity would be the width shaded divided by the total collector width.

$$\%\ \text{shading} = \frac{w_s}{w}$$

In this case, the sun is not due south, so the profile angle, $\gamma_2$, is needed, and it can be obtained from Equation 2.31. First, we need the new altitude angle ($h_s = -45°$).

$$\sin\alpha_2 = \sin L \sin\delta_s + \cos L \cos\delta_s \cos h_s$$
$$\alpha_2 = 22.7°\ (0.397\ \text{rad})$$

Next, the solar azimuth angle:

$$\sin a_s = \frac{\cos\delta_s \sin h_s}{\cos\alpha_2}$$
$$a_s = -44.7°\ (-0.780\ \text{rad})$$

Finally, the profile angle is obtained.

$$\tan\gamma_2 = \sec a_s \tan\alpha$$
$$\gamma_2 = 30.5°\ (0.532\ \text{rad})$$

From the geometry and the law of sines, we arrive at the following relation.

$$\frac{\sin(\beta+\gamma_2)}{h/\sin\alpha_1} = \frac{\sin(\alpha_1-\gamma_2)}{w_s}$$

Simplifying:

$$\frac{w_s}{w} = \frac{\sin(\alpha_1-\gamma_2)}{\sin(\beta+\gamma_2)}\frac{\sin\beta}{\sin\alpha_1}$$
$$= 0.129;\ \text{i.e.}, 12.9\%\ \text{of the collector is shaded.}$$

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