

SEFE | TEACHER'S GUIDE

SOLAR ENERGY FOR EVERYONE

A Practical Guide from Basics to System Design

Solutions, self-tests, and teaching support

● INCLUDES ANDROID APP



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First Edition | 2026

SOLAR ENERGY FOR EVERYONE

Teacher's Guide

Self-Tests, Answers, Full Solutions, and Teaching Support for Every Chapter

Companion to the SEFE Student Edition

SEFE

FOR TEACHERS AND INSTRUCTORS

First Edition — 2026

Solar Energy for Everyone: Teacher's Guide

Self-tests, answers, full solutions, and teaching support — the companion volume to the SEFE Student Edition

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This book and its companion app, Solar Energy for Everyone (SEFE), are provided free of charge for anyone who wishes to learn. Voluntary donations in support of their continued development are warmly welcomed and appreciated.

About This Guide

This Teacher's Guide is the companion volume to the Solar Energy for Everyone Student Edition. For every chapter it contains the complete self-test — each question together with its correct answer and a short explanation — and every practice problem repeated with its full, step-by-step solution.

The self-tests appear only in this guide, not in the Student Edition, so you decide when and how students meet them: in class, as homework, as a quick start-of-lesson check, or as revision before an exam. The practice problems do appear in the Student Edition, but without solutions, so students can attempt them honestly before their work is checked here.

As in the Student Edition, some numbers in the questions and problems are clearly marked example numbers for practice, and some — such as the Kurdistan Region's Project Runaki electricity tariff — are real, sourced data. See the Student Edition for the full lessons behind every topic.

Using SEFE in the Classroom

A practical rhythm that works well: one chapter per teaching week. Start the week with the chapter's learning goals, teach from the lessons, and let students work the worked examples by hand before showing the solution steps. End the week with the self-test from this guide, then assign a selection of practice problems — the Basic and Standard levels suit most students, and the Challenge problems suit stronger students or group work.

Every chapter has at least one hands-on activity marked Home, Classroom, Laboratory, or Field. These need only simple, low-cost materials, and they are where the ideas become real — treat them as part of the course, not as optional extras. The case studies in each chapter work well as short discussion starters: read them aloud and ask the class what they would have done differently.

The SEFE Android application contains the same lessons, self-tests, and problems in interactive form, plus calculators and simulations. A practical pattern for class: teach from the book, then let students check their hand calculations against the matching app calculator — the lesson text marks these moments with an "App tool" note. Students can also use the app's self-tests for private practice at any time, since the app never shows an answer before the student commits to one.

When marking, give credit for a correct method with a small arithmetic slip — the solution steps in this guide show the expected method, so partial credit is easy to judge. Where a problem uses example prices or example sun hours, a student who uses different but clearly stated assumptions and a correct method deserves full credit.

Table of Contents

About This Guide.....	4
Using SEFE in the Classroom.....	4
Table of Contents.....	5
Energy and Power in Everyday Life.....	7
Self-Test — Questions and Answers.....	7
Practice Problems — Full Solutions.....	8
Electricity Basics.....	12
Self-Test — Questions and Answers.....	12
Practice Problems — Full Solutions.....	13
The Sun and Solar Energy.....	17
Self-Test — Questions and Answers.....	17
Practice Problems — Full Solutions.....	18
How Solar Cells Work.....	22
Self-Test — Questions and Answers.....	22
Practice Problems — Full Solutions.....	23
Solar Panels in Practice.....	28
Self-Test — Questions and Answers.....	28
Practice Problems — Full Solutions.....	29
Batteries and Energy Storage.....	33
Self-Test — Questions and Answers.....	33
Practice Problems — Full Solutions.....	34
Charge Controllers.....	39
Self-Test — Questions and Answers.....	39
Practice Problems — Full Solutions.....	40
Inverters.....	45
Self-Test — Questions and Answers.....	45
Practice Problems — Full Solutions.....	46
Wiring, Protection, and Safety Equipment.....	51
Self-Test — Questions and Answers.....	51
Practice Problems — Full Solutions.....	52
Understanding Electrical Loads.....	56
Self-Test — Questions and Answers.....	56
Practice Problems — Full Solutions.....	57
Solar System Types.....	62
Self-Test — Questions and Answers.....	62
Practice Problems — Full Solutions.....	63
Off-Grid System Design.....	69
Self-Test — Questions and Answers.....	69
Practice Problems — Full Solutions.....	70
On-Grid and Hybrid System Design.....	75
Self-Test — Questions and Answers.....	75
Practice Problems — Full Solutions.....	77
Solar Water Pumping.....	82
Self-Test — Questions and Answers.....	82
Practice Problems — Full Solutions.....	83
Money and the Environment.....	87
Self-Test — Questions and Answers.....	87
Practice Problems — Full Solutions.....	88

Site Assessment and System Planning.....	92
Self-Test — Questions and Answers.....	92
Practice Problems — Full Solutions.....	93
Installation Step by Step.....	98
Self-Test — Questions and Answers.....	98
Practice Problems — Full Solutions.....	99
Testing and Commissioning.....	104
Self-Test — Questions and Answers.....	104
Practice Problems — Full Solutions.....	105
Finding and Fixing Problems.....	110
Self-Test — Questions and Answers.....	110
Practice Problems — Full Solutions.....	111
Maintenance.....	117
Self-Test — Questions and Answers.....	117
Practice Problems — Full Solutions.....	118
Solar Energy in Iraq and the Kurdistan Region.....	123
Self-Test — Questions and Answers.....	123
Practice Problems — Full Solutions.....	124
Capstone Design Projects.....	129
Self-Test — Questions and Answers.....	129
Practice Problems — Full Solutions.....	131

CHAPTER ONE

Energy and Power in Everyday Life

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is energy?

- A. The ability to do work — to move, heat, light, or change things
- B. The speed of electricity in a wire
- C. Another name for voltage

Answer: The ability to do work — to move, heat, light, or change things. Energy is the ability to do work. It comes in forms like light, heat, motion, and electricity, and it can change from one form to another.

Q2. Which unit measures power?

- A. Kilowatt-hour (kWh)
- B. Watt (W)
- C. Ampere (A)

Answer: Watt (W). Power is measured in watts (W). kWh measures energy, and amperes measure current.

Q3. kW and kWh are two names for the same thing.

Answer: False. kW is power — how fast energy is used (like speed). kWh is energy — how much is used (like distance).

Q4. A television uses 100 W and runs for 8 hours. How much energy does it use, in kWh?

Answer: 0.8 kWh (± 0.01). $E = P \times t = 100 \text{ W} \times 8 \text{ h} = 800 \text{ Wh} = 0.8 \text{ kWh}$.

Q5. Which uses the MOST energy?

- A. A 2000 W heater running 15 minutes
- B. A 100 W television running 6 hours
- C. A 10 W lamp running 24 hours

Answer: A 100 W television running 6 hours. Heater: $2000 \times 0.25 = 0.5 \text{ kWh}$. Television: $100 \times 6 = 0.6 \text{ kWh}$. Lamp: $10 \times 24 = 0.24 \text{ kWh}$. The television wins — energy depends on power AND time.

Q6. A fan uses 60 W and runs for 10 hours. How many kWh does it use?

Answer: 0.6 kWh (± 0.01). $E = P \times t = 60 \text{ W} \times 10 \text{ h} = 600 \text{ Wh} = 0.6 \text{ kWh}$.

Q7. What does your electricity bill charge you for?

- A. Kilowatts (kW)
- B. Kilowatt-hours (kWh)
- C. Volts (V)

Answer: Kilowatt-hours (kWh). The electricity meter counts energy in kWh, and the bill charges for each kWh used.

Q8. A generator subscription gives 5 amperes at 220 V. How much power is that, in watts?

Answer: 1100 W (± 5). $P = V \times I = 220 \text{ V} \times 5 \text{ A} = 1100 \text{ W}$.

Q9. A 5-ampere generator subscription (at 220 V) can run a 2000 W water heater.

Answer: False. $5 \text{ A} \times 220 \text{ V} = 1100 \text{ W}$ available. The 2000 W heater needs almost twice that, so it cannot run.

Q10. A refrigerator uses 150 W and its compressor effectively runs about 8 hours a day. How many kWh does it use per day?

Answer: 1.2 kWh (± 0.05). $E = 150 \text{ W} \times 8 \text{ h} = 1200 \text{ Wh} = 1.2 \text{ kWh}$. Remember: count the fridge's effective running hours, not 24 hours.

Q11. Which of these are units of ENERGY? (Choose all correct answers.)

- A. Joule (J)
- B. Watt (W)
- C. Watt-hour (Wh)
- D. Kilowatt-hour (kWh)

Answer: Joule (J); Watt-hour (Wh); Kilowatt-hour (kWh). Joules, watt-hours, and kilowatt-hours all measure energy. The watt measures power — how fast energy is used.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A lamp uses 20 W. It is on for 5 hours. How much energy does it use, in Wh and in kWh?

Solution

1. Write the equation: $E = P \times t$
2. Put in the numbers: $E = 20 \text{ W} \times 5 \text{ h} = 100 \text{ Wh}$
3. Convert to kWh: $100 \div 1000 = 0.1 \text{ kWh}$

The lamp uses 100 Wh, which is 0.1 kWh.

Problem 2 [Basic] Convert: (a) 3500 Wh into kWh, and (b) 2.4 kWh into Wh.

Solution

1. (a) Wh $\rightarrow$ kWh: divide by 1000. $3500 \div 1000 = 3.5 \text{ kWh}$
 2. (b) kWh $\rightarrow$ Wh: multiply by 1000. $2.4 \times 1000 = 2400 \text{ Wh}$
- (a) 3.5 kWh and (b) 2400 Wh.**

Problem 3 [Basic] A television uses 120 W and runs 4 hours every day. How much energy does it use per day and per month (30 days), in kWh?

Solution

1. Daily energy: $E = P \times t = 120 \text{ W} \times 4 \text{ h} = 480 \text{ Wh} = 0.48 \text{ kWh}$
2. Monthly energy: $0.48 \text{ kWh} \times 30 = 14.4 \text{ kWh}$

The television uses 0.48 kWh per day and 14.4 kWh per month.

Problem 4 [Basic] An electric kettle uses 2000 W and runs for 6 minutes. How much energy does it use, in kWh? (Careful: convert minutes to hours first.)

Solution

1. Convert time: 6 minutes = $6 \div 60 = 0.1 \text{ h}$
2. $E = P \times t = 2000 \text{ W} \times 0.1 \text{ h} = 200 \text{ Wh}$

3. Convert: $200 \div 1000 = 0.2 \text{ kWh}$

The kettle uses 0.2 kWh. High power, short time — moderate energy.

Problem 5 [Standard] A room has: 4 lamps of 10 W used 5 hours, a 70 W fan used 8 hours, and a 110 W television used 3 hours. Find the total daily energy in kWh.

Solution

1. Lamps: $4 \times 10 \text{ W} = 40 \text{ W}$; $E = 40 \times 5 = 200 \text{ Wh}$

2. Fan: $E = 70 \times 8 = 560 \text{ Wh}$

3. Television: $E = 110 \times 3 = 330 \text{ Wh}$

4. Total: $200 + 560 + 330 = 1090 \text{ Wh} = 1.09 \text{ kWh}$

The room uses 1.09 kWh per day.

Problem 6 [Standard] A refrigerator is rated 160 W. Its compressor effectively runs 8 hours per day. Find its daily and monthly (30 days) energy in kWh.

Solution

1. Daily: $E = 160 \text{ W} \times 8 \text{ h} = 1280 \text{ Wh} = 1.28 \text{ kWh}$

2. Monthly: $1.28 \times 30 = 38.4 \text{ kWh}$

About 1.28 kWh per day and 38.4 kWh per month — fridges matter because they run every day.

Problem 7 [Standard] A family has a 3-ampere generator subscription at 220 V. During a power cut they want to run: a 100 W television, a 160 W refrigerator, three 10 W lamps, and a 500 W washing machine. Can they?

Solution

1. Available power: $P = V \times I = 220 \times 3 = 660 \text{ W}$

2. Wanted power: $100 + 160 + (3 \times 10) + 500 = 790 \text{ W}$

3. Compare: $790 \text{ W} > 660 \text{ W}$ — too much

No. Without the washing machine the load is 290 W, which is fine. The machine must wait for grid hours.

Problem 8 [Standard] A home uses 5 kWh per day. The example electricity price is 100 IQD per kWh. (Example numbers for practice — real prices are studied in Chapter 21.) What is the monthly bill for 30 days?

Solution

1. Monthly energy: $5 \text{ kWh} \times 30 = 150 \text{ kWh}$

2. Monthly cost: $150 \times 100 = 15,000 \text{ IQD}$

The monthly bill is about 15,000 IQD in this example.

Problem 9 [Standard] Charging a phone uses about 10 W for 2 hours each day. An air conditioner uses 2000 W. For how many minutes would the AC need to run to use the same energy as a FULL MONTH of phone charging (30 days)?

Solution

1. Phone per day: $10 \text{ W} \times 2 \text{ h} = 20 \text{ Wh}$
2. Phone per month: $20 \times 30 = 600 \text{ Wh} = 0.6 \text{ kWh}$
3. AC time: $t = E \div P = 600 \text{ Wh} \div 2000 \text{ W} = 0.3 \text{ h}$
4. Convert: $0.3 \times 60 = 18 \text{ minutes}$

Just 18 minutes of AC equals a whole month of phone charging. Big appliances dominate.

Problem 10 [Challenge] A home has: 8 LED lamps (10 W, 5 h), one television (100 W, 6 h), one refrigerator (150 W, 8 h effective), two fans (70 W each, 10 h), one washing machine (500 W, 1 h), one water pump (370 W, 0.5 h). (a) Find the daily energy in kWh. (b) Find the monthly energy. (c) Which single appliance uses the most energy, and what would you check first to save energy?

Solution

1. Lamps: $8 \times 10 \times 5 = 400 \text{ Wh}$
2. Television: $100 \times 6 = 600 \text{ Wh}$
3. Refrigerator: $150 \times 8 = 1200 \text{ Wh}$
4. Fans: $2 \times 70 \times 10 = 1400 \text{ Wh}$
5. Washing machine: $500 \times 1 = 500 \text{ Wh}$
6. Water pump: $370 \times 0.5 = 185 \text{ Wh}$
7. (a) Total: $400 + 600 + 1200 + 1400 + 500 + 185 = 4285 \text{ Wh} \approx 4.3 \text{ kWh per day}$
8. (b) Monthly: $4.285 \times 30 \approx 128.6 \text{ kWh}$
9. (c) The two fans together use the most (1.4 kWh/day), then the fridge (1.2). Check fan hours first — are they running in empty rooms?

About 4.3 kWh per day and 129 kWh per month. The fans are the biggest user — usage hours matter as much as power ratings.

Problem 11 [Challenge] A 5-ampere generator subscription costs 50,000 IQD per month (example numbers). The generator runs 8 hours per day. (a) What is the maximum energy the family could receive in a month (30 days)? (b) What is the minimum cost per kWh? (c) The real average use is about half the maximum — what is the real cost per kWh? Compare with the example grid price of 100 IQD/kWh.

Solution

1. Available power: $P = 220 \times 5 = 1100 \text{ W} = 1.1 \text{ kW}$
2. (a) Maximum energy: $1.1 \text{ kW} \times 8 \text{ h} \times 30 \text{ days} = 264 \text{ kWh}$
3. (b) Minimum cost: $50,000 \div 264 \approx 190 \text{ IQD per kWh}$
4. (c) Real energy $\approx 264 \div 2 = 132 \text{ kWh}$; real cost $\approx 50,000 \div 132 \approx 380 \text{ IQD per kWh}$
5. Compare: 380 vs 100 IQD — generator energy costs about 4 times more

Generator energy costs several times more per kWh than grid energy. This calculation is the economic heart of the solar story in our region.

Problem 12 [Challenge] A family runs their AC (1800 W) for 6 hours a day. They decide to run it only 4 hours and use a 70 W fan for the other 6 hours of the evening. (a) How much energy do they save per day? (b) Per month (30 days)? (c) How much money per month at the example price of 100 IQD/kWh?

Solution

1. AC saving: $1800 \text{ W} \times 2 \text{ h} = 3600 \text{ Wh} = 3.6 \text{ kWh}$ per day

2. Fan cost: $70 \text{ W} \times 6 \text{ h} = 420 \text{ Wh} = 0.42 \text{ kWh}$ per day

3. (a) Net saving: $3.6 - 0.42 = 3.18 \text{ kWh}$ per day

4. (b) Monthly: $3.18 \times 30 = 95.4 \text{ kWh}$

5. (c) Money: $95.4 \times 100 = 9,540 \text{ IQD}$ per month

About 95 kWh and 9,540 IQD saved per month (example prices). Reducing load is always the cheapest 'power plant' — remember this when we size solar systems.

CHAPTER TWO

Electricity Basics

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is resistance?

- A. The push that moves current through a wire
- B. The property of a material that opposes the flow of current
- C. The rate at which energy is used

Answer: The property of a material that opposes the flow of current. Resistance is the property of a material that opposes the flow of current. Voltage is the push (pressure), and power is how fast energy is used.

Q2. Which unit measures resistance?

- A. Volt (V)
- B. Ampere (A)
- C. Ohm (Ω)

Answer: Ohm (Ω). Resistance is measured in ohms (Ω). Volts measure voltage, and amperes measure current.

Q3. A 24 V battery is connected across an 8 Ω resistor. What is the current, in amperes?

Answer: 3 A (± 0.1). $I = V \div R = 24 \div 8 = 3$ A.

Q4. Which formula lets you calculate power using only CURRENT and RESISTANCE (not voltage)?

- A. $P = V \times I$
- B. $P = I^2 \times R$
- C. $P = I \div R$

Answer: $P = I^2 \times R$. $P = I^2 \times R$ uses only current and resistance. $P = V \times I$ needs the voltage instead.

Q5. If you double the voltage across a resistor, keeping the resistance the same, the power exactly doubles too.

Answer: False. False. If resistance stays the same, doubling the voltage also doubles the current (Ohm's law: $I = V \div R$). Since power = voltage $\times$ current, doubling both means the power becomes four times bigger, not two times bigger.

Q6. Which of these are true about alternating current (AC)? (Choose all correct answers.)

- A. It flows in one direction only
- B. It changes direction many times per second
- C. The grid (mains) supply in Iraq is AC
- D. Its frequency in Iraq is about 50 Hz

Answer: It changes direction many times per second; The grid (mains) supply in Iraq is AC; Its frequency in Iraq is about 50 Hz. AC changes direction repeatedly, not option 1 — that describes DC. Iraq's grid supplies AC at about 50 Hz.

Q7. A solar panel produces electricity that is...

- A. AC, the same as the grid
- B. DC, and needs an inverter to power normal AC appliances
- C. Neither AC nor DC

Answer: DC, and needs an inverter to power normal AC appliances. Solar panels always produce DC electricity. Since most home appliances run on AC, an inverter is needed to convert DC to AC. You will study inverters fully in Chapter 8.

Q8. Iraq's grid supplies AC at 50 Hz. What is the period of one complete cycle, in milliseconds?

Answer: 20 ms (± 1). $T = 1 \div f = 1 \div 50 = 0.02 \text{ s} = 20 \text{ ms}$.

Q9. In a SERIES circuit with two lamps, what happens if one lamp burns out (breaks)?

- A. The other lamp keeps working normally
- B. Both lamps stop working, because the circuit path is broken
- C. Both lamps get brighter

Answer: Both lamps stop working, because the circuit path is broken. In a series circuit there is only one path for current. If one lamp breaks, the path is broken, so current cannot flow anywhere in the circuit, and both lamps go dark.

Q10. Two resistors, 5 Ω and 15 Ω , are connected in SERIES. What is the total resistance, in ohms?

Answer: 20 Ω (± 0.5). In series, resistances simply add: $R_{\text{total}} = R_1 + R_2 = 5 + 15 = 20 \Omega$.

Q11. Before measuring the RESISTANCE of a component with a multimeter, what must you do?

- A. Leave the component connected and powered on
- B. Remove or isolate the component from the circuit and make sure there is no power
- C. Nothing special — just touch the probes to the component while it is running

Answer: Remove or isolate the component from the circuit and make sure there is no power. Resistance must be measured with the component isolated from the circuit and with no power applied. Measuring resistance on a live, powered circuit gives wrong readings and can damage the meter.

Q12. To measure CURRENT with a multimeter, how must it be connected?

- A. In parallel, across the two points, like a voltage measurement
- B. In series, breaking the circuit and inserting the meter into the path
- C. It does not matter — current mode works either way

Answer: In series, breaking the circuit and inserting the meter into the path. To measure current, the multimeter must be placed in series — you break the circuit and let the current flow through the meter. Connecting current mode in parallel creates a short circuit and can blow the meter's fuse.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A 9 V battery is connected across a 3 Ω resistor. Find the current.

Solution

1. Write the equation: $I = V \div R$
2. Put in the numbers: $I = 9 \text{ V} \div 3 \Omega$
3. Calculate: $I = 3 \text{ A}$

The current is 3 A.

Problem 2 [Basic] A resistor of 15 Ω carries a current of 2 A. Find the voltage across it.

Solution

1. Write the equation: $V = I \times R$
2. Put in the numbers: $V = 2 \text{ A} \times 15 \Omega$
3. Calculate: $V = 30 \text{ V}$

The voltage across the resistor is 30 V.

Problem 3 [Basic] A small motor is connected to a 24 V supply and draws 1.5 A of current. Find the power it uses.

Solution

1. Write the equation: $P = V \times I$
2. Put in the numbers: $P = 24 \text{ V} \times 1.5 \text{ A}$
3. Calculate: $P = 36 \text{ W}$

The motor uses 36 W.

Problem 4 [Basic] Some countries use a mains frequency of 60 Hz (Iraq uses 50 Hz). Find the period of one complete cycle at 60 Hz, in milliseconds.

Solution

1. Write the equation: $T = 1 \div f$
2. Put in the numbers: $T = 1 \div 60$
3. Calculate: $T \approx 0.0167 \text{ s}$
4. Convert to milliseconds: $0.0167 \times 1000 \approx 16.7 \text{ ms}$

The period is about 16.7 ms — a little shorter than Iraq's 20 ms, because the frequency is higher.

Problem 5 [Standard] Three resistors, 2 Ω , 3 Ω , and 5 Ω , are connected in series to a 20 V battery. Find (a) the total resistance, and (b) the current from the battery.

Solution

1. (a) Total resistance: $R_{\text{total}} = R_1 + R_2 + R_3 = 2 + 3 + 5 = 10 \Omega$
2. (b) Current: $I = V \div R_{\text{total}} = 20 \div 10 = 2 \text{ A}$

The total resistance is 10 Ω , and the current from the battery is 2 A — the same current flows through all three resistors, because they are in series.

Problem 6 [Standard] Two resistors, 10 Ω and 40 Ω , are connected in parallel across a 16 V battery. Find (a) the total resistance, (b) the current in each resistor, and (c) the total current from the battery.

Solution

1. (a) $1 \div R_{\text{total}} = 1/10 + 1/40 = 4/40 + 1/40 = 5/40 = 1/8$, so $R_{\text{total}} = 8 \Omega$
2. (b) $I_1 = V \div R_1 = 16 \div 10 = 1.6 \text{ A}$, and $I_2 = V \div R_2 = 16 \div 40 = 0.4 \text{ A}$
3. (c) $I_{\text{total}} = I_1 + I_2 = 1.6 + 0.4 = 2 \text{ A}$
4. Check: $I_{\text{total}} = V \div R_{\text{total}} = 16 \div 8 = 2 \text{ A}$, which matches

The total resistance is 8 Ω , the branch currents are 1.6 A and 0.4 A, and the total current from the battery is 2 A.

Problem 7 [Standard] A wire carries 4 A of current and has a resistance of 0.5 Ω . How much power is wasted as heat in the wire?

Solution

1. Write the equation: $P = I^2 \times R$
2. Put in the numbers: $P = 4^2 \times 0.5 = 16 \times 0.5$
3. Calculate: $P = 8 \text{ W}$

8 W is wasted as heat in the wire. This is why thick, low-resistance cables are used in solar systems — thin wires waste more power as heat, as you will see in Chapter 9.

Problem 8 [Standard] A technician measures 18 V across a heater element and 3 A of current flowing through it. Find (a) the heater's resistance, and (b) the power it uses.

Solution

1. (a) $R = V \div I = 18 \div 3 = 6 \Omega$
2. (b) $P = V \times I = 18 \times 3 = 54 \text{ W}$
3. Check with the other power formula: $P = I^2 \times R = 3^2 \times 6 = 9 \times 6 = 54 \text{ W}$, which matches

The heater's resistance is 6 Ω , and it uses 54 W.

Problem 9 [Standard] A resistor of 220 Ω is connected to Iraq's home electricity supply of 220 V. Find (a) the current through it, and (b) the power it uses.

Solution

1. (a) $I = V \div R = 220 \div 220 = 1 \text{ A}$
2. (b) $P = V \times I = 220 \times 1 = 220 \text{ W}$
3. Check: $P = I^2 \times R = 1^2 \times 220 = 220 \text{ W}$, which matches

The current is 1 A, and the power used is 220 W.

Problem 10 [Challenge] A small 12 V solar lighting circuit has two LED lamps in parallel, each with an effective resistance of 24 Ω . This parallel pair is connected in series with a 4 Ω cable resistance (from a long wire run) to the 12 V battery. Find (a) the resistance of the parallel pair, (b) the total circuit resistance, (c) the total current from the battery, and (d) the voltage that actually reaches the parallel lamps.

Solution

1. (a) Parallel pair: $1 \div R_p = 1/24 + 1/24 = 2/24 = 1/12$, so $R_p = 12 \Omega$
2. (b) Total resistance: $R_{\text{total}} = R_p + R_{\text{cable}} = 12 + 4 = 16 \Omega$
3. (c) Total current: $I = V \div R_{\text{total}} = 12 \div 16 = 0.75 \text{ A}$
4. (d) Voltage at the lamps: $V_{\text{lamps}} = I \times R_p = 0.75 \times 12 = 9 \text{ V}$
5. Check: voltage dropped in the cable = $I \times R_{\text{cable}} = 0.75 \times 4 = 3 \text{ V}$, and $9 + 3 = 12 \text{ V}$, which matches the battery

The lamps only receive 9 V instead of the full 12 V, because 3 V is lost in the cable's resistance. Long, thin cables can starve solar lights of voltage — good reason to use thick, short cable runs.

Problem 11 [Challenge] A 220 V, 1000 W immersion water heater element is checked with a multimeter. Find (a) its resistance, (b) the current it draws, and (c) if it runs for 45 minutes a day, its daily energy in kWh (use $E = P \times t$ from Chapter 1).

Solution

1. (a) Resistance from power and voltage: $R = V^2 \div P = 220^2 \div 1000 = 48,400 \div 1000 = 48.4 \, \Omega$
2. (b) Current: $I = P \div V = 1000 \div 220 \approx 4.55 \, \text{A}$ (check: $V \div R = 220 \div 48.4 \approx 4.55 \, \text{A}$, which matches)
3. (c) Convert time: 45 minutes = $45 \div 60 = 0.75 \, \text{h}$
4. Daily energy: $E = P \times t = 1000 \, \text{W} \times 0.75 \, \text{h} = 750 \, \text{Wh} = 0.75 \, \text{kWh}$

The heater's resistance is about 48.4 Ω , it draws about 4.55 A, and it uses 0.75 kWh of energy per day of use.

Problem 12 [Challenge] A small off-grid cabin has three lamps connected in PARALLEL to a 12 V battery. Each lamp has a resistance of 60 Ω . Find (a) the total resistance of the three lamps, (b) the total current from the battery when all three are on, (c) what a multimeter would read at the battery terminals if one lamp burns out, and why, and (d) the new total current with only two lamps working.

Solution

1. (a) $1 \div R_{\text{total}} = 1/60 + 1/60 + 1/60 = 3/60 = 1/20$, so $R_{\text{total}} = 20 \, \Omega$
2. (b) $I_{\text{total}} = V \div R_{\text{total}} = 12 \div 20 = 0.6 \, \text{A}$
3. (c) In a parallel circuit, each branch has the full supply voltage on its own, independent of the other branches. So losing one lamp does not change the voltage — it stays at about 12 V, and the working lamps keep shining at the same brightness
4. (d) With two lamps: $1 \div R_{\text{total}} = 1/60 + 1/60 = 2/60 = 1/30$, so $R_{\text{total}} = 30 \, \Omega$, and $I_{\text{total}} = 12 \div 30 = 0.4 \, \text{A}$

The total resistance starts at 20 Ω (0.6 A total). After one lamp fails, the voltage at the remaining lamps is unchanged (about 12 V), but the total current drawn from the battery falls to 0.4 A, because there are fewer parallel paths.

CHAPTER THREE

The Sun and Solar Energy

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the approximate value of the solar constant — the power of sunlight per square meter just outside Earth's atmosphere?

- A. About 1360 W/m²
- B. About 100 W/m²
- C. About 5500 W/m²

Answer: About 1360 W/m². *The solar constant is about 1360 W/m². This is measured outside the atmosphere, facing the Sun directly — it is higher than what reaches the ground.*

Q2. On a clear day at solar noon, the irradiance reaching the ground is about the same as the solar constant.

Answer: False. *The atmosphere reflects, absorbs, and scatters sunlight. Ground-level irradiance on a clear day near solar noon is about 1000 W/m², noticeably less than the 1360 W/m² solar constant.*

Q3. Which type of radiation makes sharp, clear shadows?

- A. Direct radiation
- B. Diffuse radiation
- C. Reflected radiation

Answer: Direct radiation. *Direct radiation travels straight from the Sun without scattering, so it makes sharp shadows. Diffuse radiation comes from the whole sky and does not make sharp shadows.*

Q4. Which of these are true about diffuse radiation? (Choose all correct answers.)

- A. It comes from the whole sky, not just the Sun's direction
- B. It disappears completely on cloudy days
- C. Solar panels can still use it to make electricity
- D. It is scattered by clouds, dust, and air

Answer: It comes from the whole sky, not just the Sun's direction; Solar panels can still use it to make electricity; It is scattered by clouds, dust, and air. *Diffuse radiation is scattered sunlight that comes from the whole sky, and it is scattered by clouds, dust, and air. Solar panels can still use it — that is why panels still produce some electricity on a cloudy day, just much less than on a clear day. It does not disappear on cloudy days — on a fully cloudy day, ALL the light reaching the ground is diffuse.*

Q5. A location receives 5.5 kWh/m² of solar energy in one day. How many peak sun hours is this?

Answer: 5.5 hours (± 0.1). *Peak sun hours = daily solar energy ÷ 1 kW/m². Since 1 kW/m² is the standard, the number of peak sun hours is numerically the same as the daily energy in kWh/m²: 5.5 kWh/m² ÷ 1 kW/m² = 5.5 hours.*

Q6. A place has 4 peak sun hours on a winter day. What is the daily solar energy, in kWh/m²?

Answer: 4 kWh/m² (± 0.1). *Daily solar energy = 1 kW/m² × peak sun hours = 1 kW/m² × 4 h = 4 kWh/m².*

Q7. Why do we have seasons on Earth?

- A. Earth's axis is tilted, which changes the Sun's angle and day length through the year
- B. Earth moves closer to the Sun in summer and farther away in winter
- C. The Sun's power output changes through the year

Answer: Earth's axis is tilted, which changes the Sun's angle and day length through the year. Seasons are caused by Earth's 23.5° axial tilt, which changes the Sun's angle in the sky and the length of the day. Earth's distance from the Sun changes only a little, and it does not match the seasons — Earth is actually closest to the Sun in January.

Q8. Earth is closer to the Sun in July (Northern Hemisphere summer) than in January.

Answer: False. It is the opposite: Earth is slightly closer to the Sun in early January and slightly farther away in early July. Seasons are caused by axial tilt, not by distance from the Sun.

Q9. At the equinox, a location's latitude is 33°N. What is the Sun's approximate maximum altitude (height above the horizon) at solar noon?

- A. 57°
- B. 33°
- C. 90°

Answer: 57°. At the equinox: altitude = 90° – latitude = 90° – 33° = 57°.

Q10. Which best describes 'peak sun hours'?

- A. The number of hours the Sun is above the horizon
- B. The equivalent number of hours of standard 1000 W/m² sunlight that would give the same daily energy
- C. The exact clock time when the Sun is highest in the sky

Answer: The equivalent number of hours of standard 1000 W/m² sunlight that would give the same daily energy. Peak sun hours compress a whole day of changing irradiance into an equivalent number of hours at the standard 1000 W/m². It is not the same as the number of daylight hours, and it is not a clock time.

Q11. Which of these change how much sunlight reaches the ground at a location? (Choose all correct answers.)

- A. Latitude
- B. Clouds
- C. Dust in the air
- D. The brand of solar panel installed

Answer: Latitude; Clouds; Dust in the air. Latitude, clouds, and dust in the air all change how much sunlight reaches the ground. The brand of solar panel does not change the sunlight available — it only affects how much of that sunlight the panel can turn into electricity, which you will study in later chapters.

Q12. A clear-sky day gives 6.0 kWh/m² of solar energy. A moderate dust storm cuts this by 30%. What is the solar energy that day, in kWh/m²?

Answer: 4.2 kWh/m² (± 0.1). Energy with losses = clear-sky energy × (1 – loss fraction) = 6.0 × (1 – 0.30) = 6.0 × 0.70 = 4.2 kWh/m².

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] The solar energy at a location is 4.8 kWh/m² in one day. How many peak sun hours is this?

Solution

1. Peak sun hours = daily solar energy ÷ 1 kW/m² (the standard irradiance).
2. PSH = 4.8 kWh/m² ÷ 1 kW/m² = 4.8 hours.

The location has 4.8 peak sun hours that day.

Problem 2 [Basic] A location has 6.2 peak sun hours in one day in July. Find the daily solar energy, in kWh/m².

Solution

1. Daily solar energy = $1 \text{ kW/m}^2 \times \text{peak sun hours}$.
2. $H = 1 \text{ kW/m}^2 \times 6.2 \text{ h} = 6.2 \text{ kWh/m}^2$.

The daily solar energy is 6.2 kWh/m^2 .

Problem 3 [Basic] The solar constant is about 1360 W/m^2 . On a clear day at solar noon, ground-level irradiance is about 1000 W/m^2 . About how many W/m^2 are lost between space and the ground at that moment?

Solution

1. Write what you know: solar constant $\approx 1360 \text{ W/m}^2$; ground-level clear-noon irradiance $\approx 1000 \text{ W/m}^2$.
2. Subtract: $1360 - 1000 = 360 \text{ W/m}^2$.

About 360 W/m^2 is reflected, absorbed, or scattered by the atmosphere before reaching the ground at that moment.

Problem 4 [Basic] A test panel measuring 2 m^2 faces the Sun directly, just outside Earth's atmosphere. Using the solar constant (about 1360 W/m^2), find the power falling on the panel.

Solution

1. Write the idea: power = irradiance $\times$ area.
2. $P = 1360 \text{ W/m}^2 \times 2 \text{ m}^2 = 2720 \text{ W}$.
3. Convert to kW: $2720 \div 1000 = 2.72 \text{ kW}$.

About 2720 W , or 2.72 kW , falls on the panel.

Problem 5 [Standard] A solar site's latitude is about 30.5°N (close to Basra's latitude). Estimate the Sun's maximum altitude at solar noon on the equinox.

Solution

1. Write the equinox rule: altitude = $90^\circ - \text{latitude}$.
2. altitude = $90^\circ - 30.5^\circ = 59.5^\circ$.

The Sun reaches about 59.5° above the horizon at solar noon on the equinox at this site.

Problem 6 [Standard] Using the example annual-average peak sun hours from this chapter (Erbil 5.6 h , Baghdad 5.9 h), find the difference in daily solar energy between the two cities, and express Baghdad's advantage as a percentage of Erbil's value.

Solution

1. Find the difference: $5.9 - 5.6 = 0.3 \text{ kWh/m}^2/\text{day}$.
2. Find the percentage: $0.3 \div 5.6 \times 100 \approx 5.4\%$.

Baghdad's example daily solar energy is about 0.3 kWh/m^2 higher than Erbil's — about 5.4% more.

Problem 7 [Standard] Using the clear-sky and cloudy-sky noon irradiance values from the table in Lesson 4 (950 W/m^2 and 240 W/m^2), find the percentage reduction caused by the clouds.

Solution

1. Find the reduction: $950 - 240 = 710 \text{ W/m}^2$.
2. Find the percentage: $710 \div 950 \times 100 \approx 74.7\%$.

Thick cloud cuts the irradiance by about 74.7% at solar noon in this example.

Problem 8 [Standard] A 3 kW solar array is installed at a site with an example 5.4 peak sun hours per day. Estimate its daily energy production (ignoring losses), and its energy production over 30 days.

Solution

1. Daily energy $\approx$ array power $\times$ peak sun hours $= 3 \text{ kW} \times 5.4 \text{ h} = 16.2 \text{ kWh}$.
2. Monthly energy $= 16.2 \text{ kWh} \times 30 \text{ days} = 486 \text{ kWh}$.

The array could produce about 16.2 kWh per day, or about 486 kWh over 30 days (before real-world losses, which later chapters add in).

Problem 9 [Standard] Using this chapter's example day-length figures for Erbil — about 14.5 hours in June and about 9.5 hours in December — find how many more hours of daylight June has than December, per day and per week (7 days).

Solution

1. Daily difference: $14.5 - 9.5 = 5$ hours.
2. Weekly difference: $5 \times 7 = 35$ hours.

June days have about 5 more hours of daylight than December days — 35 more hours across a week.

Problem 10 [Challenge] Using Erbil's example peak sun hours for June (7.8 h), July (7.9 h), and August (7.6 h): (a) find the average peak sun hours for these three months, (b) find the average daily solar energy for the period in kWh/m², and (c) estimate the total energy a 2 kW array could produce over these three months (92 days), ignoring losses.

Solution

1. (a) Average PSH $= (7.8 + 7.9 + 7.6) \div 3 = 23.3 \div 3 \approx 7.77 \text{ h}$.
2. (b) Daily solar energy $= 1 \text{ kW/m}^2 \times 7.77 \text{ h} = 7.77 \text{ kWh/m}^2/\text{day}$ (same number, different meaning).
3. (c) Daily array energy $= 2 \text{ kW} \times 7.77 \text{ h} \approx 15.53 \text{ kWh/day}$.
4. Total over 92 days $= 15.53 \text{ kWh/day} \times 92 \text{ days} \approx 1429 \text{ kWh}$.

Summer peak sun hours average about 7.77 h; the 2 kW array could produce roughly 1429 kWh over these three summer months (before real-world losses).

Problem 11 [Challenge] Using the example annual-average peak sun hours (Erbil 5.6 h, Basra 6.0 h) and an example electricity price of 100 IQD/kWh (as used in Chapter 1): (a) estimate the yearly energy a 5 kWp solar system would produce in each city (ignoring losses), (b) find the difference in kWh per year, and (c) find the value of that difference in IQD per year.

Solution

1. Erbil daily energy $= 5 \text{ kW} \times 5.6 \text{ h} = 28 \text{ kWh/day}$; yearly $= 28 \times 365 = 10,220 \text{ kWh/yr}$.

2. Basra daily energy = $5 \text{ kW} \times 6.0 \text{ h} = 30 \text{ kWh/day}$; yearly = $30 \times 365 = 10,950 \text{ kWh/yr}$.

3. (b) Difference = $10,950 - 10,220 = 730 \text{ kWh/yr}$.

4. (c) Value of difference = $730 \text{ kWh} \times 100 \text{ IQD/kWh} = 73,000 \text{ IQD/yr}$.

In this example, the same 5 kWp system would produce about 730 kWh more per year in Basra than in Erbil — worth about 73,000 IQD/year at the example price. Real system output also depends on temperature, losses, and other local factors covered in later chapters.

Problem 12 [Challenge] A solar water pump in Duhok (latitude about 36.9°N) needs at least 8 hours of daylight to complete its full daily pumping cycle. Using this chapter's example day-length figures for the region (about 12 h at the equinox, about 14.5 h at the June solstice, about 9.5 h at the December solstice), decide whether the 8-hour requirement is met in each of these three example periods. Which period is the tightest (closest to failing)?

Solution

1. Compare each example day length with the 8-hour requirement: equinox $12 \text{ h} > 8 \text{ h}$ (met); June solstice $14.5 \text{ h} > 8 \text{ h}$ (met); December solstice $9.5 \text{ h} > 8 \text{ h}$ (met).

2. Find the smallest margin: December's margin is $9.5 - 8 = 1.5 \text{ h}$, smaller than the equinox's 4 h margin or June's 6.5 h margin.

The pump's 8-hour requirement is met in all three example periods, but December is the tightest case, with only about 1.5 extra hours of daylight to spare — a good reason to size a system using winter data, not summer data.

CHAPTER FOUR

How Solar Cells Work

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What does a solar (photovoltaic) cell change into electricity?

- A. Light energy from the sun
- B. Heat energy from the sun
- C. Wind energy
- D. Chemical energy from fuel

Answer: Light energy from the sun. *The photovoltaic effect changes light energy (photons) into electrical energy. It does not need heat, wind, or fuel.*

Q2. A solar (PV) cell makes electricity mainly from the sun's heat.

Answer: False. *PV cells make electricity from LIGHT, not heat. In fact, extra heat actually reduces a cell's power output, as you learned in Lesson 5.*

Q3. What is the main material used in most solar cells today?

- A. Silicon
- B. Copper
- C. Aluminum
- D. Glass

Answer: Silicon. *Silicon, a semiconductor, is the main material in most solar cells. Copper and aluminum are used for wires and frames; glass protects the cells, but neither one makes the electricity.*

Q4. Which of these are the THREE cell technologies described in this chapter? (Choose all three correct answers.)

- A. Monocrystalline
- B. Hydro-crystalline
- C. Polycrystalline
- D. Thin-film

Answer: Monocrystalline; Polycrystalline; Thin-film. *Monocrystalline, polycrystalline, and thin-film are the three cell types covered in this chapter. 'Hydro-crystalline' is not a real solar cell technology.*

Q5. Sixty cells are connected in SERIES inside a module. What happens to the voltage?

- A. It adds up — about $60 \times$ one cell's voltage
- B. It multiplies by the current
- C. It stays the same as one single cell
- D. It becomes zero

Answer: It adds up — about $60 \times$ one cell's voltage. *Connecting cells in series adds up their voltages, while the current stays the same as one cell. This is how a 0.6 V cell becomes a 30+ V module.*

Q6. When modules are connected in PARALLEL, the total current adds up, while the voltage stays the same as one module.

Answer: True. *Parallel connections add current and keep voltage the same — the opposite of series connections, which add voltage and keep current the same.*

Q7. A cell measuring $0.20\text{ m} \times 0.20\text{ m}$ receives 1000 W/m^2 of sunlight and produces 6.4 W of electrical power. What is its efficiency, in %?

Answer: 16 % (± 0.5). $\text{Area} = 0.20 \times 0.20 = 0.04\text{ m}^2$. $\text{Sunlight power} = 1000 \times 0.04 = 40\text{ W}$. $\text{Efficiency} = 6.4 \div 40 \times 100 = 16\%$.

Q8. On a datasheet, what does 'Voc' mean?

- A. Open-circuit voltage — voltage with no current flowing
- B. Voltage at the operating current
- C. Voltage divided by current
- D. The 'vocational' rating of the panel

Answer: Open-circuit voltage — voltage with no current flowing. *Voc is the open-circuit voltage — the maximum possible voltage, measured when no current is flowing. It is not the panel's normal operating voltage.*

Q9. What are Standard Test Conditions (STC)?

- A. 1000 W/m^2 irradiance, 25°C cell temperature, and AM1.5 spectrum
- B. 800 W/m^2 irradiance, 20°C air temperature, and 1 m/s wind
- C. The hottest recorded day of the year
- D. Whatever conditions the installer measures on-site

Answer: 1000 W/m^2 irradiance, 25°C cell temperature, and AM1.5 spectrum. *STC is the fixed testing standard: 1000 W/m^2 , 25°C cell temperature, AM1.5 spectrum. The second option describes NOCT conditions, not STC — a common mix-up.*

Q10. A panel is rated 300 W at STC. Its temperature coefficient of P_{max} is $-0.40\%/^\circ\text{C}$. If the cell temperature is 45°C (with full 1000 W/m^2 sunshine), what is the power output?

Answer: 276 W (± 2). $\Delta T = 45 - 25 = 20^\circ\text{C}$. $\text{Power change} = -0.40\% \times 20 = -8\%$. $\text{Power} = 300 \times (1 - 0.08) = 300 \times 0.92 = 276\text{ W}$.

Q11. As a solar cell gets hotter, it usually produces MORE power.

Answer: False. *Heat lowers Voc significantly, and this outweighs the small rise in Isc, so Pmax falls as cells get hotter — an important fact for Iraq's hot summers.*

Q12. Which TWO of these values are measured exactly AT the maximum power point (not at open-circuit or short-circuit)?

- A. V_{mp}
- B. Voc
- C. I_{mp}
- D. Isc

Answer: V_{mp} ; I_{mp} . *V_{mp} and I_{mp} are the voltage and current exactly at the maximum power point. Voc and Isc are the two extreme points, where power is actually zero.*

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A solar cell measures $0.15\text{ m} \times 0.15\text{ m}$. In full sun (1000 W/m^2), it produces 3.6 W of electrical power. What is its efficiency, in %?

Solution

1. Find the cell's area: $A = 0.15 \times 0.15 = 0.0225\text{ m}^2$

2. Find the sunlight power on it: $G \times A = 1000 \times 0.0225 = 22.5 \text{ W}$

3. Efficiency = $P_{\max} \div (G \times A) \times 100 = 3.6 \div 22.5 \times 100 = 16\%$

The cell's efficiency is 16%.

Problem 2 [Basic] A small module has 36 cells connected in series. Each cell has an open-circuit voltage of about 0.60 V. Estimate the module's open-circuit voltage (V_{oc}).

Solution

1. Write the equation: $V_{oc, \text{module}} \approx N \times V_{oc, \text{cell}}$

2. Put in the numbers: $V_{oc, \text{module}} \approx 36 \times 0.60 \text{ V}$

3. Calculate: $V_{oc, \text{module}} \approx 21.6 \text{ V}$

The module's V_{oc} is about 21.6 V — a common size for small 12 V-system modules.

Problem 3 [Basic] You need a small array with about 500 W of power. If you use modules rated 100 Wp each, how many modules do you need?

Solution

1. Divide the power needed by the power of one module: $N = 500 \text{ W} \div 100 \text{ W} = 5$

2. Check: $5 \text{ modules} \times 100 \text{ W} = 500 \text{ W}$ — matches the target

You need 5 modules of 100 Wp each.

Problem 4 [Basic] A panel is rated 100 W at STC. Its temperature coefficient of $P_{\max}$ is $-0.45\%/^{\circ}\text{C}$. If the cell temperature rises to 35°C (10°C above the 25°C STC reference), by how many watts does the power drop?

Solution

1. Find the temperature difference: $\Delta T = 35 - 25 = 10^{\circ}\text{C}$

2. Find the percentage change: $-0.45\%/^{\circ}\text{C} \times 10^{\circ}\text{C} = -4.5\%$

3. Find the watts: $100 \text{ W} \times 0.045 = 4.5 \text{ W}$

The power drops by about 4.5 W, from 100 W to about 95.5 W.

Problem 5 [Standard] A module's datasheet shows: $V_{oc} = 36.0 \text{ V}$, $I_{sc} = 8.80 \text{ A}$, $P_{\max} = 245 \text{ W}$. Find the fill factor (FF), as a percentage.

Solution

1. Write the equation: $FF = P_{\max} \div (V_{oc} \times I_{sc})$

2. Multiply the bottom: $36.0 \times 8.80 = 316.8$

3. Divide: $FF = 245 \div 316.8 = 0.773$

4. Convert to %: $0.773 \times 100 = 77.3\%$

The fill factor is about 77.3% — a healthy value for a crystalline silicon module.

Problem 6 [Standard] A module is rated 250 W ($P_{\max}$) at STC and measures $1.64 \text{ m} \times 0.99 \text{ m}$. What is its efficiency?

Solution

1. Find the area: $A = 1.64 \times 0.99 = 1.6236 \text{ m}^2$
2. Find the sunlight power: $G \times A = 1000 \times 1.6236 = 1623.6 \text{ W}$
3. Efficiency = $250 \div 1623.6 \times 100 = 15.4\%$

The module's efficiency is about 15.4%.

Problem 7 [Standard] A designer wants a string voltage as close as possible to 150 V, but NOT more than 150 V, using modules with $V_{mp} = 32.0 \text{ V}$. How many modules should be connected in series? What is the exact string voltage?

Solution

1. Divide the target voltage by one module's voltage: $150 \div 32.0 = 4.69$
2. A fifth module would push the string over the 150 V limit ($5 \times 32.0 = 160 \text{ V}$), so round DOWN to 4 modules
3. Exact string voltage: $4 \times 32.0 = 128 \text{ V}$

Use 4 modules in series; the string voltage is 128 V, safely under the 150 V limit.

Problem 8 [Standard] An 'EcoRay 300' panel is rated 300 W at STC. Its temperature coefficient of P_{max} is $-0.38\%/^{\circ}\text{C}$. On a hot day in Basra, the cell temperature reaches 68°C . Assuming full 1000 W/m^2 sunshine, what is the panel's power output?

Solution

1. Find the temperature difference: $\Delta T = 68 - 25 = 43^{\circ}\text{C}$
2. Find the percentage change: $-0.38\%/^{\circ}\text{C} \times 43^{\circ}\text{C} = -16.34\%$
3. Apply it: Power = $300 \times (1 - 0.1634) = 300 \times 0.8366$

The panel produces only about 251.0 W (down from 300 W) — a loss of about 49 W from heat alone, even in full sunshine.

Problem 9 [Standard] For a panel with $\text{NOCT} = 44^{\circ}\text{C}$, estimate the cell temperature when the ambient air temperature is 38°C and the irradiance is 700 W/m^2 .

Solution

1. Write the formula: $T_{\text{cell}} = T_{\text{ambient}} + [(\text{NOCT} - 20) \div 800] \times G$
2. Compute the bracket: $(44 - 20) \div 800 = 24 \div 800 = 0.03$
3. Multiply by G: $0.03 \times 700 = 21^{\circ}\text{C}$
4. Add the ambient temperature: $38 + 21 = 59^{\circ}\text{C}$

The estimated cell temperature is 59°C .

Problem 10 [Standard] A designer connects 4 modules in series to form one string (each module: $V_{mp} = 30.5 \text{ V}$, $I_{mp} = 8.2 \text{ A}$). Two identical strings are connected in parallel. Find: (a) the string voltage, (b) the array's total current, (c) the array's total power at maximum power point.

Solution

1. String voltage: $V_{\text{string}} = 4 \times 30.5 = 122.0 \text{ V}$
2. Array current (2 strings in parallel): $I_{\text{array}} = 2 \times 8.2 = 16.4 \text{ A}$
3. Array power: $P_{\text{array}} = 122.0 \times 16.4 = 2000.8 \text{ W}$
4. Check: 8 modules total $\times (30.5 \times 8.2 = 250.1 \text{ W each}) = 2000.8 \text{ W}$ — matches

The array produces 122.0 V, 16.4 A, and about 2000.8 W at its maximum power point.

Problem 11 [Challenge] An 'EcoRay 400' module is rated $P_{\text{max}} = 400 \text{ W}$ at STC, measures $1.90 \text{ m} \times 1.05 \text{ m}$, and has a temperature coefficient of P_{max} of $-0.35\%/^{\circ}\text{C}$. (a) Find its efficiency at STC. (b) On a summer afternoon, the irradiance is 850 W/m^2 and the cell temperature reaches 63°C . Estimate the actual power output. (Assume power scales directly with irradiance, then apply the temperature correction.)

Solution

1. (a) Area = $1.90 \times 1.05 = 1.995 \text{ m}^2$. Efficiency = $400 \div (1000 \times 1.995) \times 100 = 20.1\%$
 2. (b) Scale power for irradiance: $P = 400 \times (850 \div 1000) = 340 \text{ W}$
 3. (b) Find the temperature difference: $\Delta T = 63 - 25 = 38^{\circ}\text{C}$
 4. (b) Apply the temperature correction: $-0.35\% \times 38 = -13.3\%$; $P = 340 \times (1 - 0.133) = 340 \times 0.867$
- (a) The module's STC efficiency is about 20.1%. (b) Under 850 W/m^2 and 63°C cell temperature, it produces about 294.8 W — well below its 400 W STC rating, because lower light and high heat both reduce output.**

Problem 12 [Challenge] A manufacturer states a cell has $V_{\text{oc}} = 0.65 \text{ V}$ and $I_{\text{sc}} = 9.50 \text{ A}$, with a fill factor of 0.80. The cell's area is 243 cm^2 (0.0243 m^2). (a) Estimate the cell's maximum power (P_{max}). (b) Estimate its efficiency at STC (1000 W/m^2).

Solution

1. (a) Rearrange the fill factor equation: $P_{\text{max}} = \text{FF} \times V_{\text{oc}} \times I_{\text{sc}}$
 2. (a) Calculate: $P_{\text{max}} = 0.80 \times 0.65 \times 9.50 = 4.94 \text{ W}$
 3. (b) Find the sunlight power on the cell: $G \times A = 1000 \times 0.0243 = 24.3 \text{ W}$
 4. (b) Efficiency = $P_{\text{max}} \div (G \times A) \times 100 = 4.94 \div 24.3 \times 100 = 20.3\%$
- (a) P_{max} is about 4.94 W. (b) Efficiency is about 20.3% — a high-efficiency monocrystalline-type cell.**

Problem 13 [Challenge] A family in Duhok needs a 3000 W (3 kW) array. Option A: monocrystalline modules rated 400 W each, 1.95 m^2 per module. Option B: polycrystalline modules rated 330 W each, 1.94 m^2 per module. (a) How many modules of each type are needed (round up to a whole module)? (b) What total roof area does each option need? (c) Which option needs less roof area, and by how much?

Solution

1. Option A: modules needed = $3000 \div 400 = 7.5 \rightarrow$ round up to 8 modules (3200 W total)
 2. Option A: roof area = $8 \times 1.95 = 15.6 \text{ m}^2$
 3. Option B: modules needed = $3000 \div 330 = 9.09 \rightarrow$ round up to 10 modules (3300 W total)
 4. Option B: roof area = $10 \times 1.94 = 19.4 \text{ m}^2$
 5. Compare: $19.4 - 15.6 = 3.8 \text{ m}^2$ more for Option B
- Option A (monocrystalline) needs 8 modules and 15.6 m^2 of roof. Option B (polycrystalline) needs 10**

modules and 19.4 m² of roof — 3.8 m² more, showing why higher efficiency matters when roof space is limited.

CHAPTER FIVE

Solar Panels in Practice

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What does a solar panel's datasheet show?

- A. Only its price and brand
- B. Its electrical, mechanical, and warranty specifications, measured at standard test conditions
- C. Only the color of the panel

Answer: Its electrical, mechanical, and warranty specifications, measured at standard test conditions. A datasheet lists a panel's electrical values (like P_{max} , V_{oc} , I_{sc}), size, weight, and warranty, all measured at standard test conditions (STC), so buyers can compare panels fairly.

Q2. Which cell type is usually the MOST efficient?

- A. Polycrystalline
- B. Monocrystalline
- C. Thin-film

Answer: Monocrystalline. Monocrystalline cells, cut from a single silicon crystal, usually reach the highest efficiency (about 19–22%), ahead of polycrystalline (about 15–18%) and thin-film (about 10–13%).

Q3. A panel is rated 360 W and its area is 1.8 m². What is its efficiency, in %?

Answer: 20 % (± 0.5). $\eta = P_{max} \div (\text{Area} \times 1000) \times 100 = 360 \div (1.8 \times 1000) \times 100 = 360 \div 1800 \times 100 = 20\%$.

Q4. A panel costs \$120 and is rated 400 W. What is its cost per watt, in \$/W?

Answer: 0.3 \$/W (± 0.01). $\text{Cost per watt} = \text{Price} \div P_{max} = \$120 \div 400 \text{ W} = \$0.30/\text{W}$.

Q5. In Iraq and the Kurdistan Region (Northern Hemisphere), panels should generally face true north for the most sunlight.

Answer: False. Iraq and the Kurdistan Region are in the Northern Hemisphere, where the sun spends most of the day in the southern sky. Panels should face true south, not north, for the most sunlight.

Q6. A city is at latitude 33°N. Using the simple year-round tilt guideline, what tilt angle would you start with, in degrees?

Answer: 33 degrees (± 2). The simple year-round guideline is $\text{tilt angle} \approx \text{latitude}$, so a 33°N site starts with a tilt of about 33°.

Q7. For the BEST winter energy in the Northern Hemisphere, should the tilt angle be higher or lower than the latitude?

- A. Higher (steeper)
- B. Lower (flatter)
- C. Tilt does not matter in winter

Answer: Higher (steeper). In winter, the sun is lower in the sky, so a steeper (higher) tilt angle catches it better: $\text{winter tilt} \approx \text{latitude} + 15^\circ$.

Q8. Which of these commonly cause shading on a rooftop panel in a town or city? (Choose all correct answers.)

- A. A neighboring building
- B. A water tank on the roof
- C. Direct overhead sunlight at solar noon in summer

D. A tree branch

Answer: A neighboring building; A water tank on the roof; A tree branch. *Neighboring buildings, water tanks on the roof, and tree branches can all block sunlight from part of a panel. Direct overhead sunlight is not shading — it is exactly what a panel needs.*

Q9. A small shadow covering just a few percent of a panel's surface can only reduce its power by a similarly small percentage, because power loss is always proportional to the shaded area.

Answer: False. *Because cells are wired in series inside a panel, a small shadow on even one cell can force a whole bypass-diode group (about a third of the panel) offline, causing a much bigger loss than the shaded area alone would suggest.*

Q10. A 500 W panel has an example soiling loss of 10% after a dusty month. What is its actual power output in strong sunlight, in W?

Answer: 450 W (± 5). $P_{\text{actual}} = P_{\text{STC}} \times (1 - L_{\text{soil}}) = 500 \times (1 - 0.10) = 500 \times 0.90 = 450 \text{ W}.$

Q11. Four identical panels, each 40 V and 10 A, are connected in SERIES. What is the string's total voltage and current?

A. 160 V, 10 A

B. 40 V, 40 A

C. 160 V, 40 A

Answer: 160 V, 10 A. *In series, voltage adds ($4 \times 40 \text{ V} = 160 \text{ V}$) and current stays the same as one panel (10 A).*

Q12. Three identical strings, each producing 8 A, are connected in parallel. What is the array's total current, in A?

Answer: 24 A (± 0.5). *In parallel, current adds: $I_{\text{array}} = n_p \times I_{\text{string}} = 3 \times 8 \text{ A} = 24 \text{ A}$. Voltage would stay the same as one string.*

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A panel is rated 320 W. It measures 1.65 m $\times$ 1.00 m. What is its efficiency, in %?

Solution

1. Find the area: $A = 1.65 \times 1.00 = 1.65 \text{ m}^2$

2. Write the equation: $\eta = P_{\text{max}} \div (A \times 1000) \times 100$

3. Put in the numbers: $\eta = 320 \div (1.65 \times 1000) \times 100 = 320 \div 1650 \times 100$

4. Calculate: $\eta \approx 19.4\%$

The panel's efficiency is about 19.4%.

Problem 2 [Basic] Panel X costs \$114 (example price) and is rated 380 W. Panel Y costs \$160 (example price) and is rated 500 W. Find the cost per watt of each. Which one is cheaper per watt?

Solution

1. Panel X: cost per watt = Price $\div$ Pmax = $\$114 \div 380 \text{ W} = \$0.30/\text{W}$

2. Panel Y: cost per watt = $\$160 \div 500 \text{ W} = \$0.32/\text{W}$

3. Compare: $\$0.30/\text{W}$ is lower than $\$0.32/\text{W}$

Panel X is cheaper per watt ($\$0.30/\text{W}$ vs. $\$0.32/\text{W}$).

Problem 3 [Basic] Three identical panels, each with $V_{oc} = 45\text{ V}$, are connected in series. Find the string's open-circuit voltage.

Solution

1. Write the equation: $V_{\text{string}} = n_s \times V_{\text{panel}}$
2. Put in the numbers: $V_{\text{string}} = 3 \times 45\text{ V}$
3. Calculate: $V_{\text{string}} = 135\text{ V}$

The string's open-circuit voltage is 135 V.

Problem 4 [Basic] Four identical panels, each with $I_{sc} = 9\text{ A}$, are connected in parallel. Find the array's short-circuit current.

Solution

1. Write the equation: $I_{\text{array}} = n_p \times I_{\text{panel}}$
2. Put in the numbers: $I_{\text{array}} = 4 \times 9\text{ A}$
3. Calculate: $I_{\text{array}} = 36\text{ A}$

The array's short-circuit current is 36 A.

Problem 5 [Standard] A 350 W panel loses an example 12% of its power to dust after five weeks without cleaning. Find its actual power output in strong sunlight.

Solution

1. Write the equation: $P_{\text{actual}} = P_{\text{STC}} \times (1 - L_{\text{soil}})$
2. Change the percent to a fraction: $12\% = 0.12$
3. Put in the numbers: $P_{\text{actual}} = 350 \times (1 - 0.12) = 350 \times 0.88$
4. Calculate: $P_{\text{actual}} = 308\text{ W}$

The panel's actual output is 308 W, a loss of 42 W.

Problem 6 [Standard] Duhok is at latitude 36.9°N . Find the recommended year-round tilt, and the recommended summer and winter tilt angles, using the simple guidelines from Lesson 2.

Solution

1. Year-round: $\beta \approx \varphi = 36.9^\circ \approx 37^\circ$
2. Summer: $\beta_{\text{summer}} \approx \varphi - 15 = 36.9 - 15 = 21.9^\circ \approx 22^\circ$
3. Winter: $\beta_{\text{winter}} \approx \varphi + 15 = 36.9 + 15 = 51.9^\circ \approx 52^\circ$

Duhok's recommended tilt is about 37° year-round, 22° for summer, and 52° for winter.

Problem 7 [Standard] A designer connects 5 identical panels in series to form one string. Each panel: $V_{oc} = 41\text{ V}$, $I_{sc} = 10.5\text{ A}$, $P_{\text{max}} = 340\text{ W}$. Two such strings are connected in parallel. Find: (a) the string voltage, (b) the array current, (c) the total array power.

Solution

1. (a) String voltage: $V_{\text{string}} = n_s \times V_{\text{panel}} = 5 \times 41 = 205 \text{ V}$
2. (b) Array current: $I_{\text{array}} = n_p \times I_{\text{panel}} = 2 \times 10.5 = 21 \text{ A}$
3. (c) Total panels: $5 \times 2 = 10$ panels; total power = $10 \times 340 \text{ W} = 3400 \text{ W}$

String voltage = 205 V, array current = 21 A, total array power = 3400 W (3.4 kW).

Problem 8 [Standard] A shop wants 6 panels rated 400 W each, priced at an example \$0.32 per watt. Find (a) the total power of the array, and (b) the total cost.

Solution

1. (a) Total power: $6 \times 400 \text{ W} = 2400 \text{ W} = 2.4 \text{ kW}$
2. (b) Total cost: Price = Total power $\times$ cost per watt = $2400 \times \$0.32$
3. Calculate: Total cost = \$768

The array is 2.4 kW, at an example total cost of \$768.

Problem 9 [Standard] A panel has 60 cells and 3 bypass diodes, each protecting a group of 20 cells. A satellite dish fully shades 1 cell in one group, all day. (a) What fraction of the panel's area does that one shaded cell cover? (b) Roughly what fraction of the panel's rated power is still available while the shadow is there, and what percent loss is that?

Solution

1. (a) Shaded area fraction: $1 \div 60 \times 100 \approx 1.7\%$
2. (b) The bypass diode routes current around the whole shaded group (20 of 60 cells), so that group — about 1/3 of the panel — stops contributing power
3. Remaining power fraction: $1 - 1/3 = 2/3 \approx 67\%$; power loss: $1/3 \approx 33\%$

Even though the shadow covers only about 1.7% of the panel's area, roughly 33% of its power is lost, because a whole bypass-diode group is affected.

Problem 10 [Challenge] A family wants about 3.2 kW of solar panels for their roof. They choose a panel rated 400 W, $V_{oc} = 45 \text{ V}$, $I_{sc} = 11.5 \text{ A}$, priced at an example \$0.29/W. (a) How many panels do they need? (b) If they arrange them as 2 equal strings in parallel, how many panels are in each string? (c) Find the string's V_{oc} . (d) Find the total example cost.

Solution

1. (a) Number of panels: $3200 \text{ W} \div 400 \text{ W} = 8$ panels
2. (b) Panels per string: $8 \text{ panels} \div 2 \text{ strings} = 4$ panels per string
3. (c) String V_{oc} : $V_{\text{string}} = n_s \times V_{oc} = 4 \times 45 = 180 \text{ V}$
4. (d) Total cost: $8 \text{ panels} \times 400 \text{ W} \times \$0.29/\text{W} = 3200 \text{ W} \times \$0.29/\text{W} = \$928$

8 panels (4 in series $\times$ 2 parallel strings), string $V_{oc} = 180 \text{ V}$, total example cost = \$928.

Problem 11 [Challenge] You plan a 10-panel array. Each panel measures $2.0 \text{ m} \times 1.0 \text{ m}$ (2.0 m^2 each). The installer says to plan for 55% extra area beyond the panels' own area, for tilt frames and row spacing. How much total roof area should you plan for?

Solution

1. Total panel area: $10 \times 2.0 \text{ m}^2 = 20 \text{ m}^2$
2. Add 55% extra: 20×1.55
3. Calculate: 31 m^2

Plan for about 31 m^2 of roof area.

Problem 12 [Challenge] A 3 kW array normally produces energy as if the sun shone at full strength for an average of 4.5 hours every day (you will study this 'sun-hours' idea fully in Chapter 3). During a dusty month, soiling cuts output by an example 15% for the whole month (30 days). (a) Find the normal expected daily energy, in kWh. (b) Find the actual daily energy during the dusty month. (c) Find the total energy lost over the 30 days because of dust, in kWh.

Solution

1. (a) Normal daily energy: $E = \text{Power} \times \text{sun-hours} = 3 \text{ kW} \times 4.5 \text{ h} = 13.5 \text{ kWh}$
2. (b) Actual daily energy: $13.5 \times (1 - 0.15) = 13.5 \times 0.85 = 11.475 \approx 11.48 \text{ kWh}$
3. Daily loss: $13.5 - 11.475 = 2.025 \text{ kWh}$
4. (c) Total loss over 30 days: $2.025 \times 30 = 60.75 \text{ kWh}$

Normal output is 13.5 kWh/day; during the dusty month it drops to about 11.48 kWh/day — a loss of about 60.75 kWh (about 61 kWh) over the 30 days.

CHAPTER SIX

Batteries and Energy Storage

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. Why do most off-grid and hybrid solar systems need a battery?

- A. To store energy for use when the sun is not shining
- B. To make the solar panels produce more power
- C. To change AC electricity into DC electricity

Answer: To store energy for use when the sun is not shining. A battery stores energy made during sunny hours so it can be used at night, on cloudy days, or during a power cut.

Q2. Which of these are lead-acid battery types? (Choose all correct answers.)

- A. Flooded
- B. AGM
- C. LiFePO4
- D. Gel

Answer: Flooded; AGM; Gel. Flooded, AGM, and gel are all lead-acid types — they use the same basic chemistry, packaged differently. LiFePO4 is a lithium battery, a different chemistry.

Q3. A car (starting) battery is a good, cheap choice for a solar system.

Answer: False. Car batteries are built for one short, big burst of current, not for slow, deep, repeated discharges. Using one in a solar system ruins it in months — always use a deep-cycle battery.

Q4. A battery is rated 12 V, 150 Ah. How much total energy can it store, in Wh?

Answer: 1800 Wh (± 20). $E = V \times C = 12 \text{ V} \times 150 \text{ Ah} = 1800 \text{ Wh}$.

Q5. What does 'depth of discharge' (DoD) mean?

- A. How much of the battery's capacity has already been used
- B. How deep underground the battery is installed
- C. How fast the battery can be charged

Answer: How much of the battery's capacity has already been used. Depth of discharge (DoD) is the percentage of the battery's capacity that has been used. $\text{DoD} = 100\% - \text{state of charge}$.

Q6. A 12 V, 100 Ah lead-acid battery has a maximum safe DoD of 50%. How much usable energy does it have, in Wh?

Answer: 600 Wh (± 20). $E_{\text{usable}} = V \times C \times \text{DoD} = 12 \text{ V} \times 100 \text{ Ah} \times 0.5 = 600 \text{ Wh}$.

Q7. Which battery type usually allows the deepest safe discharge and has the longest cycle life?

- A. Flooded lead-acid
- B. AGM
- C. LiFePO4 (lithium)

Answer: LiFePO4 (lithium). LiFePO4 batteries typically allow 80–100% DoD and last thousands more cycles than lead-acid types at the same DoD.

Q8. Connecting batteries in series increases the total capacity (Ah), while the voltage stays the same.

Answer: False. *It is the opposite: series connection increases voltage while capacity stays the same as one battery. Parallel connection increases capacity while voltage stays the same.*

Q9. A design needs a 12 V, 300 Ah battery bank. Each available battery is 12 V, 100 Ah. How many batteries are needed?

Answer: 3 batteries (± 0.1). *$300 \text{ Ah} \div 100 \text{ Ah} = 3$ batteries, connected in parallel (voltage stays at 12 V, and capacity adds up).*

Q10. During the bulk charging stage, what happens?

- A. The charger sends as much safe current as it can, and voltage slowly rises
- B. The battery is already full and only a trickle current flows
- C. The battery is being discharged, not charged

Answer: The charger sends as much safe current as it can, and voltage slowly rises. *Bulk is the first stage: maximum safe current flows in, and voltage climbs. Absorption holds the voltage steady next, then float gently maintains a full battery.*

Q11. Hydrogen gas released by a charging lead-acid battery is dangerous because it can explode if it collects in a closed space and meets a spark.

Answer: True. *Hydrogen gas is invisible and has no smell, but it can explode near a spark or flame. Always charge batteries in a well-ventilated space.*

Q12. Which of these are correct safety practices for battery banks? (Choose all correct answers.)

- A. Remove metal rings and jewelry before working on the bank
- B. Charge batteries inside a closed, unventilated cupboard
- C. Fit a fuse or breaker close to the battery
- D. Keep an open flame nearby so you can see better

Answer: Remove metal rings and jewelry before working on the bank; Fit a fuse or breaker close to the battery. *Jewelry can cause short circuits, so remove it, and a fuse or breaker close to the battery protects the wiring. Hydrogen gas needs ventilation, and open flames must never be near a charging battery.*

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A battery is rated 12 V, 80 Ah. How much energy can it store, in Wh and in kWh?

Solution

1. Write the equation: $E = V \times C$
2. Put in the numbers: $E = 12 \text{ V} \times 80 \text{ Ah} = 960 \text{ Wh}$
3. Convert to kWh: $960 \div 1000 = 0.96 \text{ kWh}$

The battery can store 960 Wh, which is 0.96 kWh.

Problem 2 [Basic] A battery has a capacity of 200 Ah and a maximum depth of discharge (DoD) of 50%. How many Ah can be safely used?

Solution

1. Write the relationship: usable capacity = $C \times \text{DoD}$
2. Change percent to decimal: $50\% = 0.5$
3. Put in the numbers: usable capacity = $200 \text{ Ah} \times 0.5 = 100 \text{ Ah}$

You can safely use about 100 Ah of the battery's 200 Ah capacity.

Problem 3 [Basic] Four 12 V, 100 Ah batteries are connected in series. What is the bank's total voltage and capacity?

Solution

1. In series, voltages add: $V_{\text{bank}} = 4 \times 12 \text{ V} = 48 \text{ V}$
2. In series, capacity stays the same as one battery: 100 Ah

The bank is 48 V, 100 Ah.

Problem 4 [Basic] Six 12 V, 150 Ah batteries are connected in parallel. What is the bank's total voltage and capacity?

Solution

1. In parallel, voltage stays the same as one battery: 12 V
2. In parallel, capacity adds: $C_{\text{bank}} = 6 \times 150 \text{ Ah} = 900 \text{ Ah}$

The bank is 12 V, 900 Ah.

Problem 5 [Standard] A 12 V, 150 Ah battery has a maximum DoD of 50%. Find its usable energy, in Wh and kWh.

Solution

1. Write the equation: $E_{\text{usable}} = V \times C \times \text{DoD}$
2. Put in the numbers: $E_{\text{usable}} = 12 \text{ V} \times 150 \text{ Ah} \times 0.5$
3. Calculate: $E_{\text{usable}} = 900 \text{ Wh} = 0.9 \text{ kWh}$

The battery gives 900 Wh (0.9 kWh) of usable energy.

Problem 6 [Standard] A home needs 2000 Wh of energy from its battery bank each day, with 3 days of autonomy. The system voltage is 24 V and the batteries are lead-acid with a maximum DoD of 50%. Find the required battery bank capacity, in Ah.

Solution

1. Write the equation: $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (2000 \text{ Wh} \times 3) \div (24 \text{ V} \times 0.5)$
3. Calculate the top and bottom: $6000 \div 12$
4. Divide: $C_{\text{bank}} = 500 \text{ Ah}$

The battery bank must be at least 500 Ah at 24 V.

Problem 7 [Standard] A battery is labeled '100 Ah, C20 rate'. At the faster C10 rate, it delivers only about 90% of that rating. How many Ah can it deliver at the C10 rate?

Solution

1. Write the relationship: capacity at C10 $\approx$ rated capacity $\times$ 0.90
2. Put in the numbers: $100 \text{ Ah} \times 0.90 = 90 \text{ Ah}$

At the faster C10 rate, the battery delivers only about 90 Ah, even though it is a '100 Ah' battery.

Problem 8 [Standard] A battery bank must supply 1500 Wh per day of usable energy, with 2 days of autonomy, at 12 V, using LiFePO4 batteries with a maximum DoD of 0.8. Find the required bank capacity, in Ah.

Solution

1. Write the equation: $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (1500 \text{ Wh} \times 2) \div (12 \text{ V} \times 0.8)$
3. Calculate the top and bottom: $3000 \div 9.6$
4. Divide: $C_{\text{bank}} = 312.5 \text{ Ah}$

The bank needs at least 312.5 Ah — always round up to the next available battery size.

Problem 9 [Standard] Battery C costs 120,000 IQD and lasts about 2 years. Battery D costs 250,000 IQD and lasts about 5 years. (Example prices for practice.) Which battery costs less per year of service, and by how much?

Solution

1. Battery C per year: $120,000 \div 2 = 60,000 \text{ IQD/year}$
2. Battery D per year: $250,000 \div 5 = 50,000 \text{ IQD/year}$
3. Compare: $50,000 \text{ IQD/year} < 60,000 \text{ IQD/year}$

Battery D is the better long-term value, at 50,000 IQD per year of service (10,000 IQD/year less than Battery C), even though it costs more to buy today.

Problem 10 [Challenge] A health center needs 4800 Wh of energy from its battery bank each night, with 2 days of autonomy in case of bad weather. The system voltage is 24 V, using AGM batteries (12 V, 200 Ah each) with a maximum DoD of 50%. (a) Find the required bank capacity in Ah. (b) How many batteries are needed, and how should they be connected? (c) Find the total usable energy of the bank you designed, and check it meets the need.

Solution

1. (a) $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD}) = (4800 \times 2) \div (24 \times 0.5) = 9600 \div 12 = 800 \text{ Ah}$
2. (b) Batteries in series for voltage: $24 \text{ V} \div 12 \text{ V} = 2$ batteries per string
3. Strings in parallel for capacity: $800 \text{ Ah} \div 200 \text{ Ah} = 4$ strings
4. Total batteries: $2 \times 4 = 8$ batteries
5. (c) Usable energy = $V_{\text{sys}} \times C_{\text{bank}} \times \text{DoD} = 24 \text{ V} \times 800 \text{ Ah} \times 0.5 = 9600 \text{ Wh} = 9.6 \text{ kWh}$
6. Check: the 2-day need was $4800 \text{ Wh} \times 2 = 9600 \text{ Wh}$ — the design matches exactly

The health center needs an 800 Ah, 24 V bank — eight 12 V, 200 Ah batteries wired as 2 in series and 4 strings in parallel — giving 9.6 kWh of usable energy, exactly the two-day requirement.

Problem 11 [Challenge] A lead-acid bank gives 2400 Wh of usable energy per cycle (at its 50% DoD limit) and is rated for about 1000 cycles at that DoD. A LiFePO4 bank with the same 2400 Wh usable energy per cycle (at its 80% DoD limit) is rated for about 4000 cycles. (Typical example ratings — always check the datasheet.) The

lead-acid bank costs 1,500,000 IQD and the LiFePO₄ bank costs 4,000,000 IQD (example prices). (a) Find the total lifetime energy each bank can deliver, in kWh. (b) Find the cost per kWh of lifetime energy for each bank. Which is the better long-term value?

Solution

1. Lead-acid lifetime energy: $2400 \text{ Wh} \times 1000 \text{ cycles} = 2,400,000 \text{ Wh} = 2400 \text{ kWh}$
2. LiFePO₄ lifetime energy: $2400 \text{ Wh} \times 4000 \text{ cycles} = 9,600,000 \text{ Wh} = 9600 \text{ kWh}$
3. Lead-acid cost per kWh: $1,500,000 \text{ IQD} \div 2400 \text{ kWh} = 625 \text{ IQD/kWh}$
4. LiFePO₄ cost per kWh: $4,000,000 \text{ IQD} \div 9600 \text{ kWh} \approx 417 \text{ IQD/kWh}$
5. Compare: $417 \text{ IQD/kWh} < 625 \text{ IQD/kWh}$

Even though the LiFePO₄ bank costs much more to buy, it delivers energy over its life for about 417 IQD/kWh, cheaper than the lead-acid bank's 625 IQD/kWh — a better long-term value, if the higher upfront cost is affordable.

Problem 12 [Challenge] A technician connects three batteries in parallel to save money: a 12 V, 100 Ah flooded battery (2 years old), a 12 V, 100 Ah AGM battery (brand new), and a 12 V, 100 Ah battery from a different brand (age unknown). (a) Name two problems with this design. (b) Suggest a correct design that still gives about 12 V and 300 Ah.

Solution

1. Recall the rule from Lesson 3: always use identical batteries — same type, brand, age, and capacity — in a bank
2. Identify the problems: different chemistries and ages charge and age at different rates; the weakest battery is overstressed by the others, and mismatched batteries can develop unwanted circulating currents between them
3. Correct design: replace all three with identical new 12 V, 100 Ah batteries, same brand, model, and ideally the same batch, still connected in parallel for 12 V and 300 Ah

The mixed bank should be replaced with three identical 12 V, 100 Ah batteries (same brand, model, and age) in parallel, giving a safe 12 V, 300 Ah bank.

Problem 13 [Challenge] A mountain cabin runs these loads from its battery bank each evening: 6 LED lamps (10 W each, 5 hours), lights and a router (60 W, 5 hours), and a small fridge (75 W, effectively 8 hours). (a) Find the total daily energy needed from the battery, in Wh. (b) The owner wants 1.5 days of autonomy, a 12 V system, and LiFePO₄ batteries (DoD = 0.8). Find the required bank capacity, in Ah. (c) Available battery sizes are 100 Ah, 150 Ah, and 200 Ah (all 12 V). Using only ONE battery size in a single parallel group, which size and how many batteries meet the need with the least excess capacity?

Solution

1. (a) Lamps: $6 \times 10 \text{ W} \times 5 \text{ h} = 300 \text{ Wh}$. Router/lights: $60 \text{ W} \times 5 \text{ h} = 300 \text{ Wh}$. Fridge: $75 \text{ W} \times 8 \text{ h} = 600 \text{ Wh}$
2. (a) Total: $300 + 300 + 600 = 1200 \text{ Wh per day}$
3. (b) $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD}) = (1200 \times 1.5) \div (12 \times 0.8) = 1800 \div 9.6 = 187.5 \text{ Ah}$
4. (c) Using 100 Ah batteries: need 2 (200 Ah total). Using 150 Ah: need 2 (300 Ah total, more excess). Using 200 Ah: need only 1 (200 Ah total)
5. (c) One 200 Ah battery already covers 187.5 Ah, using the fewest batteries and connections

The cabin needs 1200 Wh per day, a 187.5 Ah bank at 12 V, and this is best met by a single 12 V, 200 Ah

LiFePO₄ battery.

CHAPTER SEVEN

Charge Controllers

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the main job of a charge controller?

- A. To convert DC electricity into AC electricity
- B. To control how the battery is charged, and protect it from overcharge and reverse current
- C. To store extra electricity for use at night

Answer: To control how the battery is charged, and protect it from overcharge and reverse current. A charge controller sits between the array and the battery. It regulates charging, stops overcharge, and blocks reverse current at night. It does not convert DC to AC (that is the inverter's job) and it does not store energy itself.

Q2. Without a charge controller, a battery can lose charge at night by pushing current backward into the solar panel.

Answer: True. This is reverse current. With no sunlight, the battery's own voltage can push current the wrong way through the panel. A charge controller has a switch that opens at night to stop this.

Q3. Which charging stage comes first, when the battery is most empty?

- A. Float
- B. Bulk
- C. Absorption

Answer: Bulk. The order is Bulk (full current, rising voltage), then Absorption (steady voltage, tapering current), then Float (gentle top-up). Bulk comes first because an empty battery can safely accept full current.

Q4. Which of these are true about PWM controllers? (Choose all correct answers.)

- A. They work best when the array's nominal voltage matches the battery's nominal voltage
- B. They use a fast on/off switch to control charging current
- C. They convert extra panel voltage into extra current
- D. They are usually cheaper than MPPT controllers

Answer: They work best when the array's nominal voltage matches the battery's nominal voltage; They use a fast on/off switch to control charging current; They are usually cheaper than MPPT controllers. PWM controllers connect the array almost directly to the battery through a fast switch, so they need matched voltages and cannot convert extra voltage into extra current — that is what MPPT does. PWM is usually the cheaper option.

Q5. A panel has $V_{mp} = 18.0\text{ V}$ and $I_{mp} = 9.0\text{ A}$. It charges a battery at 14.0 V through a PWM controller. Assuming the current stays close to I_{mp} , estimate the delivered power, in watts.

Answer: 126 W (± 3). With PWM, the panel is forced to operate near the battery voltage, not V_{mp} : $P \approx 14.0\text{ V} \times 9.0\text{ A} = 126\text{ W}$.

Q6. Which controller type can use an array wired at a much higher voltage than the battery?

- A. PWM
- B. MPPT
- C. Both work equally well for this

Answer: MPPT. An MPPT controller's DC-DC converter can safely step a higher array voltage down to the battery voltage, turning the extra voltage into extra current. A PWM controller cannot do this — it needs matched voltages.

Q7. An array's V_{mp} is 36 V. A battery is charging at 24.0 V. Using the MPPT gain estimate, what is the estimated extra energy MPPT could harvest compared to PWM, in percent?

Answer: 50 % (± 3). $Gain \approx (V_{mp} - V_{battery}) \div V_{battery} \times 100\% = (36 - 24) \div 24 \times 100\% = 50\%$.

Q8. MPPT controllers are always the best choice for every solar system, no matter the budget or system size.

Answer: False. For a small, well-matched system on a tight budget, a good PWM controller is often the smarter choice. The right controller depends on the whole system, not just the label PWM or MPPT.

Q9. What must you check about an MPPT controller before wiring several panels in series?

- A. That the total current is below the controller's minimum rating
- B. That the array's open-circuit voltage (V_{oc}) does not exceed the controller's maximum input voltage
- C. That all the panels are the same color

Answer: That the array's open-circuit voltage (V_{oc}) does not exceed the controller's maximum input voltage. Series wiring adds voltage. If the array's V_{oc} — including its higher, cold-weather value — exceeds the controller's maximum PV input voltage rating, it can permanently damage the controller.

Q10. An array has two strings wired in parallel. Each string's short-circuit current is 9.0 A. Using the standard safety factor of 1.25, find the minimum controller current rating, in amperes.

Answer: 22.5 A (± 0.5). Parallel strings add current: $I_{SC}(\text{array}) = 2 \times 9.0 \text{ A} = 18.0 \text{ A}$. Minimum controller rating = $18.0 \text{ A} \times 1.25 = 22.5 \text{ A}$.

Q11. A family has a flooded lead-acid battery. Which setting should they use only occasionally, and never on a sealed (AGM/gel) or lithium battery?

- A. Float charging
- B. Equalization
- C. Bulk charging

Answer: Equalization. Equalization is a controlled overcharge used sometimes on flooded lead-acid batteries. It can dry out a sealed battery or seriously damage a lithium battery, so it must never be used on those types.

Q12. Which of these should be checked or set correctly for good, safe charging? (Choose all correct answers.)

- A. The controller's current rating, at or above the array's $I_{sc} \times 1.25$
- B. The correct battery type (profile) setting on the controller
- C. The array's V_{oc} staying within the controller's maximum input voltage limit
- D. The color of the solar panel's frame

Answer: The controller's current rating, at or above the array's $I_{sc} \times 1.25$; The correct battery type (profile) setting on the controller; The array's V_{oc} staying within the controller's maximum input voltage limit. Current rating, battery type setting, and the voltage limit all affect safety and performance. The frame color makes no electrical difference.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A small array has one string of panels. Its short-circuit current is 8.0 A. Using the standard safety factor of 1.25, find the minimum controller current rating.

Solution

1. Write the equation: $I_{\text{controller(min)}} = I_{\text{SC}} \times 1.25$
2. Put in the numbers: $I_{\text{controller(min)}} = 8.0 \text{ A} \times 1.25$
3. Calculate: $I_{\text{controller(min)}} = 10.0 \text{ A}$

The controller must be rated at least 10.0 A. A standard 10 A controller exactly meets this.

Problem 2 [Basic] A panel's $V_{\text{mp}} = 17.0 \text{ V}$ and $I_{\text{mp}} = 8.0 \text{ A}$, so its rated power is 136 W. A PWM controller forces it to operate at the battery's charging voltage of 13.0 V. Assuming the current stays close to I_{mp} , estimate the delivered power, and the percent of rated power delivered.

Solution

1. Rated power: $P = V_{\text{mp}} \times I_{\text{mp}} = 17.0 \text{ V} \times 8.0 \text{ A} = 136 \text{ W}$
2. Delivered power with PWM: $P \approx V_{\text{battery}} \times I_{\text{mp}} = 13.0 \text{ V} \times 8.0 \text{ A} = 104 \text{ W}$
3. Percent of rated power: $104 \div 136 \times 100\% \approx 76.5\%$

About 104 W is delivered — about 76.5% of the panel's 136 W rated power.

Problem 3 [Basic] Three panels, each with $V_{\text{oc}} = 21.0 \text{ V}$, are wired in series to form one string. What is the string's total open-circuit voltage?

Solution

1. Series wiring adds voltage: $V_{\text{oc(string)}} = 3 \times 21.0 \text{ V}$
2. Calculate: $V_{\text{oc(string)}} = 63.0 \text{ V}$

The string's total open-circuit voltage is 63.0 V.

Problem 4 [Basic] Three panels, each with $I_{\text{sc}} = 8.5 \text{ A}$, are wired in parallel. What is the total short-circuit current?

Solution

1. Parallel wiring adds current: $I_{\text{SC(total)}} = 3 \times 8.5 \text{ A}$
2. Calculate: $I_{\text{SC(total)}} = 25.5 \text{ A}$

The total short-circuit current is 25.5 A.

Problem 5 [Standard] An array has 3 strings wired in parallel. Each string has 2 panels wired in series. Each panel: $I_{\text{sc}} = 8.8 \text{ A}$, $V_{\text{oc}} = 20.5 \text{ V}$. Find (a) the array's total I_{sc} , (b) the array's total V_{oc} , and (c) the minimum controller current rating using the 1.25 safety factor, with a standard size chosen from 10, 20, 30, 40, 50, 60, 80, 100 A.

Solution

1. (a) Strings are in parallel, so current adds: $I_{\text{SC(array)}} = 3 \times 8.8 \text{ A} = 26.4 \text{ A}$
2. (b) Panels within a string are in series, so voltage adds: $V_{\text{oc(string)}} = 2 \times 20.5 \text{ V} = 41.0 \text{ V}$. All 3 strings are identical and in parallel, so the array's V_{oc} is also 41.0 V.
3. (c) Apply the safety factor: $I_{\text{controller(min)}} = 26.4 \text{ A} \times 1.25 = 33.0 \text{ A}$. The next standard size at or above 33.0 A is 40 A.

The array's total I_{sc} is 26.4 A and its V_{oc} is 41.0 V. The controller needs at least 33.0 A, so choose a standard 40 A controller.

Problem 6 [Standard] A high-voltage MPPT array has $V_{mp} = 72.0$ V. A 48 V nominal battery bank is charging at 56.0 V. Estimate the MPPT energy gain over PWM, in percent.

Solution

1. Write the equation: $\text{Gain} \approx (V_{mp} - V_{battery}) \div V_{battery} \times 100\%$
2. Put in the numbers: $\text{Gain} \approx (72.0 - 56.0) \div 56.0 \times 100\%$
3. Calculate: $\text{Gain} \approx 16.0 \div 56.0 \times 100\% \approx 28.6\%$

MPPT could harvest about 28.6% more energy than PWM in this case — and PWM could not even use this wiring plan well, since 72 V is far above the battery's nominal voltage.

Problem 7 [Standard] A technician checks a controller charging a 12 V flooded battery through the day. In the morning, the voltage climbs steadily while the current stays at its maximum. By late morning, the voltage reaches 14.4 V and holds there while the current slowly drops. In the afternoon, the voltage drops to 13.5 V and stays there with only a small current flowing. Name the three stages, in the order they happened.

Solution

1. Morning (voltage climbing, current at maximum) matches Bulk — the controller pushes as much current as it can while the battery is not yet full.
2. Late morning (voltage holds steady at 14.4 V, current drops) matches Absorption — the controller holds the set voltage and lets current taper.
3. Afternoon (voltage drops to a lower 13.5 V, small current) matches Float — the controller gently maintains a full battery.

The stages, in order, are Bulk, then Absorption, then Float.

Problem 8 [Standard] A family installs 2 identical panels wired in parallel ($I_{sc} = 9.0$ A each). They plan to add 2 more identical panels in parallel next year, making 4 panels total in parallel. (a) Find today's minimum controller current rating (safety factor 1.25). (b) Find next year's minimum controller current rating after the panels are added. Choose standard sizes from 10, 20, 30, 40, 50, 60, 80, 100 A for both.

Solution

1. (a) Today: $I_{SC}(\text{array}) = 2 \times 9.0 \text{ A} = 18.0 \text{ A}$. Minimum rating = $18.0 \times 1.25 = 22.5 \text{ A}$. The next standard size at or above 22.5 A is 30 A.
2. (b) Next year: $I_{SC}(\text{array}) = 4 \times 9.0 \text{ A} = 36.0 \text{ A}$. Minimum rating = $36.0 \times 1.25 = 45.0 \text{ A}$. The next standard size at or above 45.0 A is 50 A.

A 30 A controller is enough today, but a 50 A controller is needed after the panels are added next year. Buying the 50 A controller now would avoid a second purchase later.

Problem 9 [Standard] A 24 V nominal battery bank is charged by an array with $V_{mp} = 36$ V, through a PWM controller. The battery charges at 28.0 V. (a) Estimate the percent of rated power the PWM controller can actually deliver (assume current stays about the same). (b) Would MPPT be a clearly better choice here? Estimate the MPPT gain to support your answer.

Solution

1. (a) With PWM, the delivered voltage is close to the battery voltage (28.0 V) instead of the panel's rated V_{mp} (36.0 V). Since current stays about the same, power scales with voltage: $28.0 \div 36.0 \times 100\% \approx 77.8\%$.
2. (b) MPPT gain estimate: $(36.0 - 28.0) \div 28.0 \times 100\% \approx 28.6\%$.

PWM would only deliver about 77.8% of the array's rated power here. MPPT would recover most of that gap, harvesting about 28.6% more energy — a clearly better choice for this voltage mismatch.

Problem 10 [Challenge] A small business in Duhok installs an array of six panels, each rated: $V_{oc} = 21.6$ V, $I_{sc} = 9.8$ A. They are wired as 3 strings of 2 panels in series, all 3 strings in parallel, charging a 24 V battery bank through an MPPT controller. The controller's datasheet lists a maximum PV input voltage of 100 V. On a cold morning, assume the array's V_{oc} rises by 8% above its rated value. (a) Find the array's total I_{sc} . (b) Find the minimum controller current rating (safety factor 1.25), and choose a standard size from 10, 20, 30, 40, 50, 60, 80, 100 A. (c) Find the array's V_{oc} at standard conditions, and on the cold morning. (d) Is the controller's 100 V maximum input voltage safe in both cases? Explain.

Solution

1. (a) The 3 strings are in parallel, so current adds: $I_{SC}(\text{array}) = 3 \times 9.8 \text{ A} = 29.4 \text{ A}$
2. (b) Apply the safety factor: $29.4 \text{ A} \times 1.25 = 36.75 \text{ A}$. The next standard size at or above 36.75 A is 40 A.
3. (c) Each string is 2 panels in series, so $V_{oc}(\text{string}) = 2 \times 21.6 \text{ V} = 43.2 \text{ V}$. This is also the array's V_{oc} , since parallel strings do not add voltage. On the cold morning: $43.2 \text{ V} \times 1.08 \approx 46.66 \text{ V}$, about 46.7 V.
4. (d) Compare both values with the 100 V limit: 43.2 V and 46.7 V are both far below 100 V.

The array needs a 40 A controller. Its V_{oc} is 43.2 V normally and about 46.7 V on a cold morning — both comfortably safe under the controller's 100 V maximum input voltage.

Problem 11 [Challenge] A 24 V nominal array has $V_{mp} = 34.0$ V on a hot afternoon, but $V_{mp} = 38.5$ V on a cool winter morning, because heat lowers a panel's voltage. The battery charges at 27.0 V in both cases. (a) Estimate the MPPT gain over PWM on the hot afternoon. (b) Estimate the MPPT gain on the cool morning. (c) In which condition does MPPT help more, and why does that make sense?

Solution

1. (a) Hot afternoon: Gain $\approx (34.0 - 27.0) \div 27.0 \times 100\% = 7.0 \div 27.0 \times 100\% \approx 25.9\%$
2. (b) Cool morning: Gain $\approx (38.5 - 27.0) \div 27.0 \times 100\% = 11.5 \div 27.0 \times 100\% \approx 42.6\%$
3. (c) The cool morning has the larger gap between V_{mp} and the battery voltage (11.5 V, versus 7.0 V on the hot afternoon), so MPPT has more extra voltage to turn into extra current.

MPPT helps more on the cool morning (about 42.6% gain) than on the hot afternoon (about 25.9% gain), because cold weather raises panel voltage and widens the gap MPPT can use.

Problem 12 [Challenge] A rural clinic needs a 12 V battery bank charged by 4 panels ($V_{oc} = 22.0$ V, $I_{sc} = 9.5$ A, $V_{mp} = 18.0$ V each). Two wiring plans are possible. Plan A: all 4 panels wired in parallel. Plan B: 2 strings of 2 panels in series, with the 2 strings wired in parallel. (a) For Plan A, find the array's I_{sc} , V_{oc} , and V_{mp} . (b) For Plan B, find the array's I_{sc} , V_{oc} , and V_{mp} . (c) Which plan suits a PWM controller, and which needs MPPT? Explain using the nominal-voltage-matching rule. (d) For the plan that suits PWM, find the minimum controller current rating (safety factor 1.25), and choose a standard size from 10, 20, 30, 40, 50, 60, 80, 100 A.

Solution

1. (a) Plan A has 4 panels in parallel (each its own 1-panel string). Parallel adds current, but not voltage: $I_{SC} = 4 \times 9.5 \text{ A} = 38.0 \text{ A}$, while V_{oc} and V_{mp} stay the same as one panel: $V_{oc} = 22.0 \text{ V}$, $V_{mp} = 18.0 \text{ V}$.
2. (b) Plan B has 2 strings of 2 panels in series, 2 strings in parallel. Series adds voltage per string: $V_{oc}(\text{string}) = 2 \times 22.0 \text{ V} = 44.0 \text{ V}$, $V_{mp}(\text{string}) = 2 \times 18.0 \text{ V} = 36.0 \text{ V}$. Parallel strings add current: $I_{SC}(\text{array}) = 2 \times 9.5 \text{ A} = 19.0 \text{ A}$.
3. (c) Plan A keeps the array's V_{mp} at 18.0 V, close to a 12 V battery's charging voltage (about 14.4 V) — a good match for PWM. Plan B doubles the voltage to $V_{mp} = 36.0 \text{ V}$, far above 14.4 V, which would waste a large share of power with PWM — this plan needs MPPT.
4. (d) For Plan A with PWM: $I_{\text{controller}}(\text{min}) = 38.0 \text{ A} \times 1.25 = 47.5 \text{ A}$. The next standard size at or above 47.5 A is 50 A.

Plan A (all parallel) suits PWM and needs a 50 A controller. Plan B (series strings) needs an MPPT controller instead, because of its much higher array voltage.

CHAPTER EIGHT

Inverters

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What does an inverter do?

- A. Changes AC electricity into DC electricity
- B. Changes DC electricity into AC electricity
- C. Stores electrical energy for later use

Answer: Changes DC electricity into AC electricity. *An inverter changes DC electricity (from solar panels and batteries) into AC electricity, so normal appliances can use it. Storing energy is the job of the battery (Chapter 6).*

Q2. Iraq's public grid supplies AC at a frequency of 50 Hz. What is the period of one cycle, in seconds?

Answer: 0.02 s (± 0.001). $T = 1 \div f = 1 \div 50 \text{ Hz} = 0.02 \text{ s}$ (20 milliseconds) per cycle.

Q3. Which inverter waveform most closely copies the smooth AC wave from the public grid?

- A. Square wave
- B. Modified sine wave
- C. Pure sine wave

Answer: Pure sine wave. *A pure sine wave inverter produces a smooth curve that closely matches grid power — the best, and usually the most expensive, waveform quality.*

Q4. Which of these loads run best, and most safely, on a pure sine wave inverter rather than a modified sine wave inverter? (Choose all correct answers.)

- A. A simple resistive lamp
- B. A refrigerator compressor motor
- C. A water pump motor
- D. A sensitive computer or medical device

Answer: A refrigerator compressor motor; A water pump motor; A sensitive computer or medical device. *Motors (fridge compressors, water pumps) and sensitive electronics can run hotter, noisier, or be damaged on a modified sine wave. A simple resistive lamp barely notices the difference.*

Q5. A modified sine wave inverter is a safe long-term choice for a water pump motor that runs for many hours every day.

Answer: False. *A motor that runs for long hours on a poor-quality waveform runs hotter. Over time this can damage the motor's insulation and become a fire risk. Choose pure sine wave for motors with long run times.*

Q6. A grid-tie inverter automatically switches off during a grid power cut. What is this safety feature called?

- A. Anti-islanding
- B. Low-voltage disconnect
- C. Temperature compensation

Answer: Anti-islanding. *Anti-islanding protects repair workers, who assume power lines are dead during an outage. It is required by law and by design on grid-tie inverters.*

Q7. Which inverter type is built to manage solar, battery, AND the grid or a generator together, automatically choosing the best source?

- A. Off-grid inverter
- B. Grid-tie inverter
- C. Hybrid inverter

Answer: Hybrid inverter. A hybrid inverter (often also an inverter-charger) works with solar, battery, and grid/generator together. This is why hybrid inverter-chargers are so popular in Iraqi and Kurdistan Region markets, where families deal with grid, generator, and now solar power.

Q8. An inverter takes in 1500 W of DC power and delivers 1350 W of AC power to the loads. What is its efficiency, in percent?

Answer: 90 % (± 1). $\eta = (P_{out} \div P_{in}) \times 100 = (1350 \div 1500) \times 100 = 90\%$.

Q9. An inverter's efficiency is always the same number, no matter how small or large the connected load is.

Answer: False. Efficiency changes with load. It is usually lowest with a very small load and highest somewhere in the middle of the inverter's range, then may dip slightly near full load.

Q10. A refrigerator's compressor motor has a running power of 150 W and a starting surge factor of about 4 times. What is its surge power?

- A. 150 W
- B. 375 W
- C. 600 W

Answer: 600 W. $\text{Surge power} = \text{running power} \times \text{surge factor} = 150 \text{ W} \times 4 = 600 \text{ W}$.

Q11. A home's loads add up to 800 W of continuous power. Using a 25% safety margin, what is the minimum continuous inverter rating needed, in watts?

Answer: 1000 W (± 10). $\text{Minimum continuous rating} = \text{total running watts} \times (1 + \text{margin}) = 800 \times 1.25 = 1000 \text{ W}$.

Q12. Which of these should you check before buying an inverter for a solar system with a battery? (Choose all correct answers.)

- A. The continuous power rating covers the running loads plus a safety margin
- B. The surge power rating covers the largest motor's starting surge
- C. The inverter's DC input voltage matches the battery bank voltage
- D. The inverter's color matches the wall paint

Answer: The continuous power rating covers the running loads plus a safety margin; The surge power rating covers the largest motor's starting surge; The inverter's DC input voltage matches the battery bank voltage. Continuous rating, surge rating, and matching DC input voltage to the battery bank are all essential checks before buying. The inverter's color has no effect on electrical performance.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A trader imports a batch of inverters originally made for a 60 Hz market, but Iraq's grid standard is 50 Hz. What is the period of one AC cycle at 60 Hz, and how does it compare with the period at Iraq's 50 Hz (0.02 s)?

Solution

1. Write the equation: $T = 1 \div f$

2. Put in the numbers: $T = 1 \div 60 \text{ Hz}$
3. Calculate: $T \approx 0.0167 \text{ s}$ (about 16.7 ms)
4. Compare: Iraq's 50 Hz period is 0.02 s (20 ms) — the 60 Hz period is shorter, because a higher frequency packs more cycles into every second

One cycle at 60 Hz takes about 0.0167 seconds (16.7 ms), a little shorter than the 0.02 second (20 ms) period at Iraq's 50 Hz standard. A higher frequency always means a shorter period.

Problem 2 [Basic] A homeowner has a modified sine wave inverter left over from an old UPS. They want to power: (a) three LED lamps, and (b) a small refrigerator whose compressor motor runs for many hours a day. For each load, say whether the modified sine wave inverter is a safe long-term choice, and give one reason.

Solution

1. LED lamps are a simple, low-power load with no motor; modified sine wave inverters run this kind of load without much trouble
2. The refrigerator has a compressor motor that runs many hours every day; on a modified sine wave, motors run hotter and less efficiently, and the extra heat can damage the motor's insulation over time (a fire risk too)
3. Compare the two: a resistive load is fine on modified sine wave, but a long-running motor load needs pure sine wave

The lamps can safely stay on the modified sine wave inverter. The refrigerator's compressor should be moved to a pure sine wave inverter, because long motor run-times on a poor waveform create heat and a real risk of damage.

Problem 3 [Basic] An inverter takes in 500 W of DC power from the battery and delivers 450 W of AC power to the loads. What is its efficiency, in percent?

Solution

1. Write the equation: $\eta = (P_{\text{out}} \div P_{\text{in}}) \times 100$
2. Put in the numbers: $\eta = (450 \div 500) \times 100$
3. Calculate: $\eta = 90\%$

The inverter is 90% efficient — 10% of the DC input power is lost as heat inside the inverter.

Problem 4 [Basic] A fan motor runs at 80 W. Lesson 3's table gives a typical starting surge of about 2 times the running power for a fan. What surge power should the inverter be able to supply the moment this fan starts?

Solution

1. Write the relationship: surge power = running power $\times$ surge factor
2. Put in the numbers: surge power = $80 \text{ W} \times 2$
3. Calculate: surge power = 160 W

The fan needs about 160 W of surge power for the moment it starts, even though it only needs 80 W once it is running steadily.

Problem 5 [Standard] A small shop runs these loads together during the day: 8 LED lamps (10 W each), 2 ceiling fans (70 W each), and a laptop charger (60 W). (a) Find the total continuous load. (b) Find the minimum continuous inverter rating, using a 25% safety margin.

Solution

1. Lamps: $8 \times 10 \text{ W} = 80 \text{ W}$
2. Fans: $2 \times 70 \text{ W} = 140 \text{ W}$
3. Total continuous load: $80 + 140 + 60 = 280 \text{ W}$
4. Add the 25% margin: $280 \times 1.25 = 350 \text{ W}$

The shop's continuous load is 280 W. With a 25% safety margin, the inverter needs a minimum continuous rating of 350 W. (None of these loads has a motor, so no separate surge check is needed here.)

Problem 6 [Standard] A small clinic room runs a split air conditioner (compressor running power 900 W, starting surge about 4× its running power) together with 3 LED lamps (10 W each) and a small vaccine fridge (100 W, already running steadily before the AC starts). (a) Find the total continuous load. (b) Find the minimum continuous inverter rating with a 25% margin. (c) Find the minimum surge rating needed when the AC compressor starts.

Solution

1. Continuous loads: AC 900 W + lamps (3×10) 30 W + fridge 100 W = 1030 W
2. Add the 25% margin: $1030 \times 1.25 = 1287.5 \rightarrow$ round up to 1288 W minimum continuous rating
3. AC surge: $900 \text{ W} \times 4 = 3600 \text{ W}$
4. Other loads already on when the AC starts: $30 + 100 = 130 \text{ W}$ (lamps and fridge, both already running)
5. Minimum surge rating: $130 + 3600 = 3730 \text{ W}$

The clinic's continuous load is 1030 W, giving a minimum continuous inverter rating of about 1288 W. The AC compressor's surge pushes the minimum surge rating up to 3730 W — always check the surge, especially for air conditioners and other motor loads.

Problem 7 [Standard] A family currently has grid power for about 10 hours a day and a diesel generator for the rest. They want to add solar panels and a battery, and they want their lights, refrigerator, and Wi-Fi router to keep working even during the hours when BOTH the grid and the generator are off. Which inverter type should they choose — off-grid, grid-tie, or hybrid? Give two reasons.

Solution

1. A grid-tie inverter needs the public grid to operate, and its anti-islanding safety feature switches it off during any grid outage — it gives no backup power at all, so it fails their main requirement
 2. An off-grid inverter would give backup power, but it never uses the family's existing grid connection, wasting a resource they are already paying for
 3. A hybrid inverter (inverter-charger) can use solar first, battery next, and the grid or generator only when needed, keeping essential loads running through any outage while still using the grid when it is available
- The family should choose a hybrid inverter (inverter-charger). It is the only type built to combine solar, battery, grid, and generator power, and to keep essential loads like lights, the fridge, and the router running through any outage.**

Problem 8 [Standard] A UPS nameplate shows '1000 VA / 600 W'. A technician wants to connect six devices rated 150 W each (900 W total) at the same time, reasoning that 900 is less than the 1000 VA rating. Is the technician correct? What is the real maximum power, in watts, this UPS can safely deliver?

Solution

1. Remember: W is the real, usable power rating of the equipment. VA can be a higher number, especially for loads with motors, but it never raises the safe real-power limit
2. The UPS's real power limit is the W number: 600 W, not the 1000 VA number
3. Six 150 W devices need 900 W of real power. 900 W is far more than the 600 W limit, even though 900 is less than 1000

The technician is incorrect. This UPS can safely deliver at most 600 W of real power — the 1000 VA number does not raise that limit. Connecting 900 W of devices would overload it.

Problem 9 [Standard] A hybrid inverter is 92% efficient. It needs to deliver 600 W of AC power to a home's essential loads during a power cut. How much DC power must it draw from the battery?

Solution

1. Rearrange the efficiency equation: $P_{in} = P_{out} \div \eta$
2. Change 92% to a decimal: 0.92
3. Put in the numbers: $P_{in} = 600 \text{ W} \div 0.92$
4. Calculate: $P_{in} \approx 652 \text{ W}$

The battery must supply about 652 W of DC power to deliver 600 W of usable AC power — about 52 W is lost as heat inside the inverter.

Problem 10 [Challenge] An off-grid inverter is 88% efficient. In the evening it delivers 250 W of AC power to the loads for 4 hours. (a) How much DC power must the battery supply? (b) How much DC energy (in Wh) does the battery supply over the 4 hours? (c) How much AC energy (in Wh) do the loads actually receive? (d) How much energy is lost as heat inside the inverter, in Wh, over the 4 hours?

Solution

1. DC input power: $P_{in} = P_{out} \div \eta = 250 \text{ W} \div 0.88 \approx 284 \text{ W}$
2. DC energy over 4 hours: $E_{DC} = P_{in} \times t = 284 \text{ W} \times 4 \text{ h} \approx 1136 \text{ Wh}$
3. AC energy actually delivered: $E_{AC} = P_{out} \times t = 250 \text{ W} \times 4 \text{ h} = 1000 \text{ Wh}$
4. Energy lost as heat: $E_{DC} - E_{AC} = 1136 - 1000 = 136 \text{ Wh}$

The battery supplies about 284 W (1136 Wh over 4 hours) so that the loads receive 1000 Wh of usable AC energy — about 136 Wh is lost as heat inside the inverter during those 4 hours. This is the same idea as Chapter 1's $E = P \times t$, applied on both sides of the inverter.

Problem 11 [Challenge] A home wants to run, at the same time in the evening: 10 LED lamps (10 W each), a television (120 W), a refrigerator (140 W running, starting surge about 4×), a washing machine (500 W running, starting surge about 3×), and 2 ceiling fans (70 W each). The fridge and the washing machine do not start at exactly the same moment as each other. (a) Find the total continuous load. (b) Find the minimum continuous inverter rating with a 25% margin. (c) Find the minimum surge rating, checking BOTH the fridge and the washing machine as the motor that is starting, and using the larger result. (d) Using Lesson 4's table of commercial sizes, what is the smallest suitable inverter (continuous / surge)?

Solution

1. Continuous loads: lamps $10 \times 10 = 100$ W; TV 120 W; fridge 140 W; washing machine 500 W; fans $2 \times 70 = 140$ W. Total = $100 + 120 + 140 + 500 + 140 = 1000$ W
 2. Add the 25% margin: $1000 \times 1.25 = 1250$ W minimum continuous rating
 3. If the fridge starts: fridge surge = $140 \times 4 = 560$ W; other loads already on = $1000 - 140 = 860$ W; surge needed = $860 + 560 = 1420$ W
 4. If the washing machine starts: washing machine surge = $500 \times 3 = 1500$ W; other loads already on = $1000 - 500 = 500$ W; surge needed = $500 + 1500 = 2000$ W
 5. The washing machine gives the larger surge requirement, 2000 W — this is the minimum surge rating to design for
 6. From the table, a 1000 W/2000 W inverter's continuous rating (1000 W) is too small (need 1250 W); the next size, 1500 W continuous / 3000 W surge, covers both 1250 W and 2000 W with room to spare
- The home's continuous load is 1000 W, needing a minimum continuous rating of 1250 W. Checking both motors, the washing machine's start (2000 W) needs a bigger surge allowance than the fridge's start (1420 W), so 2000 W is the number to design for. The smallest suitable commercial inverter is 1500 W continuous / 3000 W surge — always check every motor, not just the biggest running load.**

Problem 12 [Challenge] A poultry farm shed uses a 1500 W water pump motor (starting surge about $5 \times$ its running power) to fill a header tank each evening, together with 4 LED lamps (10 W each) for lighting the shed at the same time. (a) Find the minimum continuous inverter rating, using a 25% margin. (b) Find the minimum surge rating. (c) The farm owner already has a spare inverter rated 2000 W continuous / 3000 W surge. Is it big enough for this pump? If not, which rating — continuous or surge — is the problem, and by how much is it short?

Solution

1. Continuous loads: pump 1500 W + lamps (4×10) 40 W = 1540 W
 2. Add the 25% margin: $1540 \times 1.25 = 1925$ W minimum continuous rating
 3. Pump surge: $1500 \times 5 = 7500$ W
 4. Other loads already on when the pump starts: 40 W (just the lamps)
 5. Minimum surge rating: $40 + 7500 = 7540$ W
 6. Compare with the spare inverter: continuous $2000 \text{ W} \geq 1925 \text{ W}$ needed (fine); surge 3000 W is far below the 7540 W needed — short by $7540 - 3000 = 4540$ W
- The pump needs a minimum continuous rating of 1925 W and a minimum surge rating of 7540 W. The owner's spare inverter (2000 W / 3000 W) has enough continuous power, but its surge rating is short by 4540 W — a single large motor like this pump can make a spare inverter from another job completely unsuitable. Always check the surge rating for every new motor load.**

CHAPTER NINE

Wiring, Protection, and Safety Equipment

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. If a cable is made LONGER, but the current and cross-sectional area stay the same, what happens to the voltage drop?

- A. It increases
- B. It decreases
- C. It stays exactly the same

Answer: It increases. $V_{\text{drop}} = (2 \times \rho \times L \times I) \div A$. Voltage drop is directly proportional to length — a longer cable always has a bigger voltage drop for the same current and size.

Q2. Which cable can safely carry MORE current: a 2.5 mm² cable or a 6 mm² cable (same material and installation)?

- A. The 2.5 mm² cable
- B. The 6 mm² cable
- C. They always carry exactly the same current

Answer: The 6 mm² cable. A bigger cross-sectional area means lower resistance and a higher current rating (ampacity). The 6 mm² cable can safely carry more current than the 2.5 mm² cable.

Q3. A fuse can simply be reset and reused after it blows, just like a circuit breaker.

Answer: False. A blown fuse's metal strip has melted — it must be replaced. A circuit breaker has a mechanical switch and can be reset and reused.

Q4. It is safe to use a normal AC-rated circuit breaker on a DC solar circuit, as long as its current rating is high enough.

Answer: False. Current rating is not enough. DC current never crosses zero, so a DC arc does not extinguish itself the way an AC arc does. Always use a device clearly marked and rated for DC.

Q5. Which of these devices are built to stop OVERCURRENT (too much current)? Choose all correct answers.

- A. Fuse
- B. Circuit breaker
- C. RCD (residual current device)
- D. Disconnect switch

Answer: Fuse; Circuit breaker. Fuses and breakers stop overcurrent (overload or short circuit). An RCD detects current leaking to earth (a shock risk), not overcurrent. A disconnect switch is a manual on/off switch — it does not react automatically.

Q6. A 4 mm² copper cable carries 20 A over a one-way distance of 5 m. Using $\rho = 0.0175 \Omega \cdot \text{mm}^2/\text{m}$, find the voltage drop in volts.

Answer: 0.875 V (± 0.03). $V_{\text{drop}} = (2 \times \rho \times L \times I) \div A = (2 \times 0.0175 \times 5 \times 20) \div 4 = 3.5 \div 4 = 0.875 \text{ V}$.

Q7. A 24 V DC circuit carries a design current of 15 A over a one-way distance of 6 m. The maximum allowed voltage drop is 3%. Using $\rho = 0.0175 \Omega \cdot \text{mm}^2/\text{m}$, find the MINIMUM cross-sectional area needed, in mm² (before rounding to a standard size).

Answer: 4.375 mm² (± 0.1). Allowed voltage drop: $3\% \times 24 \text{ V} = 0.72 \text{ V}$. $A_{\text{min}} = (2 \times \rho \times L \times I) \div V_{\text{allow}} = (2 \times 0.0175 \times 6 \times 15) \div 0.72 = 3.15 \div 0.72 = 4.375 \text{ mm}^2$ (round up to the standard size 6 mm² in real work).

Q8. A standard RCD used to protect a person from electric shock typically trips at about what current? Answer in milliamps (mA).

Answer: 30 mA (± 5). About 30 mA is the standard trip current for personal-protection RCDs — small enough, and fast enough, to stop a dangerous shock before serious harm.

Q9. Why must a circuit breaker or fuse's current rating be LESS THAN OR EQUAL TO the cable's current rating (ampacity)?

- A. So the breaker or fuse trips before the cable can overheat
- B. So the cable never carries any current at all
- C. Because breakers are always cheaper to buy than cable

Answer: So the breaker or fuse trips before the cable can overheat. The rule is $I_{\text{design}} \leq I_{\text{device}} \leq I_{\text{cable}}$. If the device's rating were higher than the cable's rating, the cable could overheat before the device ever trips.

Q10. What is the main safety job of an RCD (residual current device)?

- A. To protect a person from electric shock by detecting current leaking to earth
- B. To protect the cable from overheating due to overcurrent
- C. To convert DC electricity into AC electricity

Answer: To protect a person from electric shock by detecting current leaking to earth. An RCD compares the current going out on live with the current returning on neutral. A difference means current is leaking somewhere — often through a person — so it switches off in a fraction of a second.

Q11. It is safe to unplug an MC4 connector by hand at any time, even while the panel is producing full current in bright sunlight.

Answer: False. A panel in sunlight is 'live' even with no switch turned on. Unplugging a loaded MC4 connector by hand can create a dangerous arc. Use a rated DC disconnect, or cover the panel first.

Q12. A cable easily passes the current-rating (ampacity) check. It can still be the WRONG size for what other reason?

- A. Excessive voltage drop over a long cable run
- B. Because it is the wrong colour
- C. Because every cable needs its own dedicated fuse box

Answer: Excessive voltage drop over a long cable run. Current rating and voltage drop are two separate checks. A cable can be thick enough to carry the current safely, yet still cause a large, wasteful voltage drop over a long distance — always check both.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] Using the current-rating table from Lesson 1 (1.5 mm² = 18 A, 2.5 mm² = 25 A, 4 mm² = 32 A, 6 mm² = 41 A, 10 mm² = 57 A), what is the smallest standard cable size that can safely carry 30 A?

Solution

1. Check 2.5 mm²: rated 25 A. Is 25 A ≥ 30 A? No — too small.
2. Check 4 mm²: rated 32 A. Is 32 A ≥ 30 A? Yes — this size is safe.

The smallest standard cable that safely carries 30 A is 4 mm² (rated 32 A).

Problem 2 [Basic] A DC circuit's design current (safety margin already included) is 12 A. Choose the smallest standard breaker size from this list that is not less than the design current: 6, 10, 13, 16, 20, 25 A.

Solution

1. Check 10 A: is $10 \geq 12$? No.
2. Check 13 A: is $13 \geq 12$? Yes — this is the smallest size that satisfies the rule.

The smallest suitable standard breaker is 13 A.

Problem 3 [Basic] A cable is rated for 32 A. A fuse protecting this cable is rated 40 A. Is this a safe combination? Explain why or why not.

Solution

1. Apply the rule: $I_{\text{device}} \leq I_{\text{cable}}$.
2. Compare: 40 A (fuse) vs 32 A (cable) — 40 A is GREATER than 32 A, so the rule fails.
3. This means the cable could overheat while carrying more current than it can safely handle, before the fuse ever blows.

Unsafe. The fuse should be 32 A or smaller (for example, a standard 25 A or 32 A fuse) to protect this cable properly.

Problem 4 [Basic] A cable's voltage drop is measured as 0.6 V in a 12 V system. What is the voltage drop as a percentage of the system voltage?

Solution

1. Write the relationship: voltage drop % = $(V_{\text{drop}} \div V_{\text{system}}) \times 100$
2. Put in the numbers: $(0.6 \div 12) \times 100 = 5\%$

The voltage drop is 5% of the system voltage.

Problem 5 [Standard] A 6 mm² copper cable runs 12 m (one-way) from an array to a charge controller, carrying 18 A. Using $\rho = 0.0175 \Omega \cdot \text{mm}^2/\text{m}$, find the voltage drop in volts.

Solution

1. Write the equation: $V_{\text{drop}} = (2 \times \rho \times L \times I) \div A$
2. Put in the numbers: $V_{\text{drop}} = (2 \times 0.0175 \times 12 \times 18) \div 6$
3. Calculate the top: $2 \times 0.0175 \times 12 \times 18 = 7.56$
4. Divide: $V_{\text{drop}} = 7.56 \div 6 = 1.26 \text{ V}$

The voltage drop is 1.26 V.

Problem 6 [Standard] A 24 V DC circuit carries a design current of 10 A over a one-way distance of 20 m. The maximum allowed voltage drop is 3%. Using $\rho = 0.0175 \Omega \cdot \text{mm}^2/\text{m}$, find the minimum cross-sectional area (before rounding), and state the standard cable size you would choose.

Solution

1. Find the allowed voltage drop in volts: $3\% \times 24 \text{ V} = 0.72 \text{ V}$
2. Write the equation: $A_{\text{min}} = (2 \times \rho \times L \times I) \div V_{\text{allow}}$

3. Put in the numbers: $A_{\min} = (2 \times 0.0175 \times 20 \times 10) \div 0.72 = 7 \div 0.72 \approx 9.72 \text{ mm}^2$

4. Round UP to the next standard size: 10 mm²

The minimum cross-section is about 9.72 mm², so the standard cable size to use is 10 mm².

Problem 7 [Standard] A solar array has a short-circuit current (I_{sc}) of 9 A. Using a 25% safety margin, find the design current. Then, using the current-rating table ($1.5 \text{ mm}^2 = 18 \text{ A}$, $2.5 \text{ mm}^2 = 25 \text{ A}$, $4 \text{ mm}^2 = 32 \text{ A}$), find the smallest cable size that meets the CURRENT rating alone.

Solution

1. Find the design current: $I_{\text{design}} = I_{\text{expected}} \times (1 + m) = 9 \times 1.25 = 11.25 \text{ A}$

2. Check 1.5 mm^2 : rated 18 A. Is $18 \text{ A} \geq 11.25 \text{ A}$? Yes — this size passes the current-rating check.

The design current is 11.25 A, and 1.5 mm^2 already meets the current-rating check. Remember: the voltage-drop check (Lesson 2) must still be done separately.

Problem 8 [Standard] An inverter draws 2500 W continuously from a 24 V battery bank. Find the DC current ($I = P \div V$), add a 25% safety margin to find the design current, and choose the smallest suitable fuse from this list: 100, 125, 150, 175 A.

Solution

1. Find the current: $I = P \div V = 2500 \text{ W} \div 24 \text{ V} \approx 104.17 \text{ A}$

2. Add the safety margin: $I_{\text{design}} = 104.17 \times 1.25 \approx 130.2 \text{ A}$

3. Check the list: $125 \text{ A} < 130.2 \text{ A}$, so it fails. $150 \text{ A} \geq 130.2 \text{ A}$, so it passes.

The design current is about 130.2 A, so the smallest suitable standard fuse is 150 A.

Problem 9 [Standard] A home's distribution board has a 32 A main breaker and a 30 mA RCD. During a fault, 45 mA of current flows to earth through a person's body. Will the RCD detect this and trip? Explain your answer.

Solution

1. An RCD trips when the leakage current is at or above its rated trip current.

2. Compare: 45 mA (leakage) vs 30 mA (RCD rating) — 45 mA is greater than 30 mA.

Yes, the RCD will detect the 45 mA leakage and trip quickly, helping to protect the person. The 32 A main breaker would NOT react to this, because 45 mA is far too small to look like an overcurrent fault.

Problem 10 [Challenge] A solar array has $I_{sc} = 12 \text{ A}$. The one-way cable distance from the array to the charge controller is 18 m, and the system voltage is 24 V. Use a 25% safety margin for the design current, $\rho = 0.0175 \Omega \cdot \text{mm}^2/\text{m}$ for copper, and a maximum allowed voltage drop of 3%. (a) Find the design current. (b) Using the current-rating table ($1.5 \text{ mm}^2 = 18 \text{ A}$, $2.5 \text{ mm}^2 = 25 \text{ A}$, $4 \text{ mm}^2 = 32 \text{ A}$), find the smallest cable that meets the CURRENT rating. (c) Check the voltage drop for that cable size in volts and as a percentage — does it meet the 3% limit? (d) If not, find the minimum cross-section for the voltage-drop limit, and state the standard cable size to use.

Solution

1. (a) Design current: $I_{\text{design}} = 12 \times 1.25 = 15 \text{ A}$

2. (b) Check 1.5 mm^2 (18 A): $18 \geq 15$, so it passes the current-rating check

3. (c) Voltage drop: $V_{\text{drop}} = (2 \times 0.0175 \times 18 \times 15) \div 1.5 = 9.45 \div 1.5 = 6.3 \text{ V}$
4. (c) As a percentage: $(6.3 \div 24) \times 100 = 26.25\%$ — far above the 3% limit, so 1.5 mm^2 FAILS
5. (d) Allowed voltage drop: $3\% \times 24 = 0.72 \text{ V}$
6. (d) $A_{\text{min}} = (2 \times 0.0175 \times 18 \times 15) \div 0.72 = 9.45 \div 0.72 \approx 13.13 \text{ mm}^2$
7. (d) Round UP to the next standard size: 16 mm^2

The design current is 15 A. By current rating alone, 1.5 mm^2 looks fine, but it fails the voltage-drop check badly (26.25%, versus the 3% limit). The minimum cross-section for the voltage-drop limit is about 13.13 mm^2 , so the cable to use is 16 mm^2 .

Problem 11 [Challenge] A hybrid inverter's AC output circuit has a continuous design current of 18 A. The AC cable chosen for this circuit is rated for 25 A. (a) Choose a suitable AC breaker from these standard sizes: 10, 13, 16, 20, 25, 32 A. (b) The circuit also needs an RCD for shock protection. What standard RCD trip current would you choose? (c) Give ONE reason this system also needs a surge protection device (SPD), even though it already has a breaker and an RCD.

Solution

1. (a) Apply the rule $I_{\text{design}} \leq I_{\text{device}} \leq I_{\text{cable}}$: $18 \text{ A} \leq I_{\text{device}} \leq 25 \text{ A}$
 2. (a) Check 16 A: is $16 \geq 18$? No. Check 20 A: is $20 \geq 18$? Yes, and $20 \leq 25$ — both conditions met
 3. (b) A standard personal-protection RCD trips at about 30 mA
 4. (c) A breaker or fuse reacts to sustained overcurrent, and an RCD reacts to earth leakage current — neither is designed to react to a voltage spike lasting a tiny fraction of a second. Only an SPD is built to sense and divert that surge safely to earth, protecting sensitive electronics.
- (a) 20 A breaker. (b) 30 mA RCD. (c) Fuses, breakers, and RCDs do not protect against lightning or switching surges — that is the SPD's specific job.**

Problem 12 [Challenge] A small solar water pump's array has $I_{\text{sc}} = 10 \text{ A}$. The one-way DC cable run from the array to the controller is 25 m, and the system voltage is 12 V. Use a 25% design margin, $\rho = 0.0175 \Omega \cdot \text{mm}^2/\text{m}$, and a tighter maximum allowed voltage drop of 2% (this circuit is critical for the pump to work reliably). (a) Find the design current. (b) Find the minimum cross-section required by the voltage-drop limit. (c) State the standard cable size to use. (d) Using that final cable size and the current-rating table ($35 \text{ mm}^2 = 125 \text{ A}$, $50 \text{ mm}^2 = 150 \text{ A}$), confirm the cable is also safe for current.

Solution

1. (a) Design current: $I_{\text{design}} = 10 \times 1.25 = 12.5 \text{ A}$
2. (b) Allowed voltage drop: $2\% \times 12 \text{ V} = 0.24 \text{ V}$
3. (b) $A_{\text{min}} = (2 \times 0.0175 \times 25 \times 12.5) \div 0.24 = 10.9375 \div 0.24 \approx 45.57 \text{ mm}^2$
4. (c) Round UP to the next standard size after 35 mm^2 : 50 mm^2
5. (d) From the table, 50 mm^2 is rated for about 150 A, which is far more than the 12.5 A design current — the current-rating check is easily satisfied

The design current is only 12.5 A, but the long 25 m run at 12 V and the tight 2% limit force a 50 mm^2 cable — the voltage-drop check, not the current-rating check, decides the size. This is why long 12 V DC runs are often avoided in favour of a higher system voltage or a controller placed closer to the array.

CHAPTER TEN

Understanding Electrical Loads

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the main purpose of a load audit?

- A. A complete, organized list of every electrical device, its power, and how it is used — the first step of solar design
- B. A test that measures the voltage of the electricity grid
- C. A report that a generator company sends every month

Answer: A complete, organized list of every electrical device, its power, and how it is used — the first step of solar design. A load audit lists every appliance with its power and use pattern. It is always the starting point, because a solar system must be sized to match real energy needs.

Q2. A borehole pump is switched on for 5 hours a day, but it does not run constantly — its duty cycle is 60%. What are its effective running hours?

Answer: 3 h (± 0.1). $t_{\text{eff}} = DC \times t_{\text{on}} = 0.60 \times 5 \text{ h} = 3 \text{ h}$. The pump's motor is actually working for 3 of those 5 hours.

Q3. A device rated 800 W is used for 2 hours each time, 3 days a week. Find its average daily energy in Wh, averaged over the full week.

Answer: 685.7 Wh (± 5). $E_{\text{day}} = (P \times t \times d) \div 7 = (800 \times 2 \times 3) \div 7 = 4800 \div 7 \approx 685.7 \text{ Wh}$.

Q4. The connected load and the peak load of a home are usually the same number.

Answer: False. Connected load adds up every appliance's rated power as if all were on at once. Peak load is the real highest value, found from the load profile — normally much lower, because appliances do not all run together.

Q5. What does a home's demand factor tell you?

- A. What fraction of the connected load is actually running at the busiest moment
- B. How many amperes the generator subscription provides
- C. How many hours of sunlight the location receives

Answer: What fraction of the connected load is actually running at the busiest moment. Demand factor = peak load $\div$ connected load. It shows how much of the 'if everything ran at once' total is really used at the busiest moment.

Q6. A small workshop has a connected load of 2000 W. Its measured peak load is 1200 W. Find its demand factor, as a percent.

Answer: 60 % (± 2). $DF = P_{\text{peak}} \div P_{\text{connected}} = 1200 \div 2000 = 0.60 = 60\%$.

Q7. Why is a home's daily energy use usually much higher in summer than in winter, in Iraq and the Kurdistan Region?

- A. Because electricity meters run faster in hot weather
- B. Because the air conditioner adds a large number of watt-hours, running for many hours a day
- C. Because the sun produces less energy in summer

Answer: Because the air conditioner adds a large number of watt-hours, running for many hours a day. An air conditioner is a very high-power appliance (often 1500–2500 W) that can run for 6–8+ hours a day in summer heat. Its energy (watts $\times$ hours) is usually far larger than every other appliance combined.

Q8. Which of these are usually good ways to reduce daily energy use BEFORE sizing a solar system? (Choose all correct answers.)

- A. Replace old bulbs with LED bulbs
- B. Replace a fixed-speed air conditioner with an inverter-type air conditioner
- C. Turn off lights and fans in empty rooms
- D. Buy a bigger solar array and more batteries

Answer: Replace old bulbs with LED bulbs; Replace a fixed-speed air conditioner with an inverter-type air conditioner; Turn off lights and fans in empty rooms. LED bulbs, efficient (inverter) appliances, and turning off unused loads all reduce the energy actually needed. Buying a bigger system does not reduce the load — it just pays more to cover a wasteful one. Reduce load first.

Q9. A phone charger left plugged into the wall, with no phone attached, normally uses zero power.

Answer: False. Most chargers and electronics use a small amount of standby power (often 0.3–0.5 W) even when 'off'. It is small per device, but it adds up over a month across a whole home.

Q10. During a power cut, which of these is usually the most CRITICAL load in a typical home?

- A. Refrigerator
- B. Washing machine
- C. Electric water heater

Answer: Refrigerator. A refrigerator protects food from spoiling and is usually treated as essential. Washing machines and water heaters are high power but can safely wait for grid or generator hours.

Q11. At 8 PM, a home has these appliances running at the same time: a refrigerator (50 W average), three lamps (10 W each), and a television (100 W). Nothing else is on. What is the load at that moment?

Answer: 180 W (± 2). Add every appliance running at that moment: $50 + (3 \times 10) + 100 = 50 + 30 + 100 = 180$ W.

Q12. Wiring a small 'critical loads panel' with only the refrigerator and a few lights lets a family use a smaller, cheaper backup inverter and battery.

Answer: True. A critical-loads-only backup only needs to supply a small peak load and daily energy, instead of the whole home's — often ten times smaller, which usually costs much less.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A borehole water pump is connected for 6 hours a day. Its duty cycle is 50% (it switches on and off automatically). Find its effective running hours.

Solution

1. Write the equation: $t_{\text{eff}} = \text{DC} \times t_{\text{on}}$
2. Put in the numbers: $t_{\text{eff}} = 0.50 \times 6$ h
3. Calculate: $t_{\text{eff}} = 3$ h

The pump's effective running time is 3 hours a day.

Problem 2 [Basic] An electric iron is rated 1000 W. It is used for 30 minutes (0.5 h) each time, 3 days a week. Find its average daily energy, in Wh, averaged over the week.

Solution

1. Write the equation: $E_{\text{day}} = (P \times t \times d) \div 7$
2. Put in the numbers: $E_{\text{day}} = (1000 \text{ W} \times 0.5 \text{ h} \times 3) \div 7$
3. Calculate the top: $1000 \times 0.5 \times 3 = 1500$
4. Divide: $1500 \div 7 \approx 214.3 \text{ Wh}$

The iron uses about 214.3 Wh per day, averaged over the week.

Problem 3 [Basic] A home has these appliances: refrigerator 150 W, ceiling fan 60 W, LED lights 80 W (total), television 100 W, and washing machine 500 W. Find the home's connected load.

Solution

1. Connected load is the sum of every appliance's rated power, as if all were on at once.
2. Add them: $150 + 60 + 80 + 100 + 500$
3. Calculate step by step: $150+60=210$; $+80=290$; $+100=390$; $+500=890 \text{ W}$

The connected load is 890 W.

Problem 4 [Basic] At a certain moment, these appliances are running together: a refrigerator (50 W, currently running), two lamps (10 W each), and a fan (70 W). What is the load at that moment?

Solution

1. List every appliance ON at that moment: 50, 10, 10, 70
2. Add them: $50 + 10 + 10 + 70$

The load at that moment is 140 W.

Problem 5 [Standard] A shop has two cycling appliances, both plugged in all day (24 h available): a display fridge rated 120 W with a 40% duty cycle, and a small freezer rated 100 W with a 50% duty cycle. Find their combined daily energy.

Solution

1. Fridge effective hours: $0.40 \times 24 = 9.6 \text{ h}$; energy = $120 \text{ W} \times 9.6 \text{ h} = 1152 \text{ Wh}$
2. Freezer effective hours: $0.50 \times 24 = 12 \text{ h}$; energy = $100 \text{ W} \times 12 \text{ h} = 1200 \text{ Wh}$
3. Add them: $1152 + 1200 = 2352 \text{ Wh}$

The fridge and freezer together use 2352 Wh (about 2.35 kWh) per day.

Problem 6 [Standard] A small workshop has a connected load of 1500 W. Its demand factor is 40%. Find its peak load.

Solution

1. Write the equation: $DF = P_{\text{peak}} \div P_{\text{connected}}$, so $P_{\text{peak}} = DF \times P_{\text{connected}}$
2. Put in the numbers: $P_{\text{peak}} = 0.40 \times 1500 \text{ W}$
3. Calculate: $P_{\text{peak}} = 600 \text{ W}$

The workshop's peak load is 600 W.

Problem 7 [Standard] A small shop has a constant background load of 40 W (a security light and a small display fridge). From 07:00 to 09:00, it also runs a 1500 W coffee machine. From 17:00 to 21:00, it turns on extra shop lights (50 W) and a till/computer (90 W), on top of the background load. Find (a) the shop's total daily energy in kWh, and (b) its peak load.

Solution

1. 00:00–07:00 (7h): 40 W → 280 Wh. 07:00–09:00 (2h): 40+1500=1540 W → 3080 Wh.
2. 09:00–17:00 (8h): 40 W → 320 Wh. 17:00–21:00 (4h): 40+50+90=180 W → 720 Wh. 21:00–24:00 (3h): 40 W → 120 Wh.
3. Add all the energies: 280+3080+320+720+120 = 4520 Wh = 4.52 kWh
4. Compare all the period powers — the highest is 1540 W, during the coffee machine's hours

Daily energy ≈ 4.52 kWh. Peak load = 1540 W, during the morning coffee machine hours — not the evening.

Problem 8 [Standard] A shop has 8 old bulbs rated 60 W each, used 5 hours a day. It replaces them with 8 LED bulbs rated 9 W each, giving the same light, still used 5 hours a day. Find (a) the daily energy saving, and (b) the monthly saving (30 days), in kWh.

Solution

1. Old energy: $8 \times 60 \text{ W} \times 5 \text{ h} = 2400 \text{ Wh/day}$
2. New energy: $8 \times 9 \text{ W} \times 5 \text{ h} = 360 \text{ Wh/day}$
3. (a) Daily saving: $2400 - 360 = 2040 \text{ Wh} = 2.04 \text{ kWh}$
4. (b) Monthly saving: $2.04 \times 30 = 61.2 \text{ kWh}$

The LED bulbs save about 2.04 kWh per day, or 61.2 kWh per month.

Problem 9 [Standard] A home leaves 10 small chargers and devices plugged in all day, each using 0.3 W of standby power. Find (a) the monthly standby energy in kWh, and (b) its cost at the example price of 100 IQD per kWh (example price, as in Chapter 1).

Solution

1. Total standby power: $10 \times 0.3 \text{ W} = 3 \text{ W}$
2. Daily energy: $3 \text{ W} \times 24 \text{ h} = 72 \text{ Wh}$
3. Monthly energy: $72 \times 30 = 2160 \text{ Wh} = 2.16 \text{ kWh}$
4. Cost at the example price: $2.16 \times 100 = 216 \text{ IQD}$

Standby power costs about 216 IQD a month in this example — small, but avoidable.

Problem 10 [Challenge] A shop currently has: fluorescent tube lights (160 W total, 10 h/day), a display fridge (200 W rated, 45% duty cycle, 24 h available), a fixed-speed air conditioner (1800 W, 6 h/day), and a computer/till (80 W, 10 h/day). The owner replaces the tube lights with LED tubes (72 W total, same hours) and the air conditioner with an inverter type (average 1100 W, same hours). Find (a) the daily energy before, (b) the daily energy after, and (c) the percentage reduction.

Solution

1. Before: lights $160 \times 10 = 1600 \text{ Wh}$; fridge $200 \times 0.45 \times 24 = 2160 \text{ Wh}$; AC $1800 \times 6 = 10800 \text{ Wh}$; computer $80 \times 10 = 800 \text{ Wh}$. Total = $1600 + 2160 + 10800 + 800 = 15360 \text{ Wh} = 15.36 \text{ kWh}$

2. After: lights $72 \times 10 = 720$ Wh; fridge unchanged 2160 Wh; AC $1100 \times 6 = 6600$ Wh; computer unchanged 800 Wh. Total = $720 + 2160 + 6600 + 800 = 10280$ Wh = 10.28 kWh
3. Saving: $15360 - 10280 = 5080$ Wh = 5.08 kWh
4. Percentage: $5080 \div 15360 \times 100 \approx 33.1\%$

Daily energy falls from 15.36 kWh to 10.28 kWh — a saving of about 5.08 kWh, or 33.1%.

Problem 11 [Challenge] A family picks these critical loads for power cuts: a refrigerator (120 W running power, 40% duty cycle), 2 safety lights (10 W each, used 4 h/day), and a router (8 W, always on). The whole home's connected load (all appliances) is 2360 W. Find (a) the critical peak load, (b) the critical daily energy in kWh, and (c) the critical peak load as a percentage of the whole home's connected load.

Solution

1. (a) Critical peak load — use the refrigerator's running power, not its average: $120 + (2 \times 10) + 8 = 120 + 20 + 8 = 148$ W
2. (b) Refrigerator daily energy: $120 \times 0.40 \times 24 = 1152$ Wh. Lights: $2 \times 10 \times 4 = 80$ Wh. Router: $8 \times 24 = 192$ Wh. Total = $1152 + 80 + 192 = 1424$ Wh = 1.424 kWh
3. (c) Percentage: $148 \div 2360 \times 100 \approx 6.3\%$

Critical peak load = 148 W and critical daily energy $\approx$ 1.424 kWh — only about 6.3% of the whole home's connected load.

Problem 12 [Challenge] A school laboratory has: LED tube lights (180 W total, 6 h/day, 08:00–14:00), 15 computers (120 W each, 5 h/day, 09:00–14:00), a chemical-storage fridge (150 W rated, 40% duty cycle, 24 h available), an air conditioner (1600 W, 6 h/day, 08:00–14:00), and a projector (200 W, 2 h/day, 15:00–17:00, a separate afternoon class). Find (a) the total daily energy in kWh, (b) the peak load during 09:00–14:00 (when lights, computers, the fridge, and the AC all overlap — use the fridge's running power for this check), (c) the connected load, (d) the demand factor, and (e) the critical-load peak if the fridge and 2 of the LED tubes (18 W each) are marked critical.

Solution

1. (a) Daily energy: lights $180 \times 6 = 1080$ Wh; computers $(15 \times 120 = 1800 \text{ W}) \times 5 \text{ h} = 9000$ Wh; fridge $150 \times 0.40 \times 24 = 1440$ Wh; AC $1600 \times 6 = 9600$ Wh; projector $200 \times 2 = 400$ Wh. Total = $1080 + 9000 + 1440 + 9600 + 400 = 21520$ Wh = 21.52 kWh
2. (b) Peak load (09:00–14:00, projector not running then): lights 180 + computers 1800 + fridge running 150 + AC 1600 = 3730 W
3. (c) Connected load (every rated power, including the projector even though it runs at a different time): $180 + 1800 + 150 + 1600 + 200 = 3930$ W
4. (d) Demand factor: $3730 \div 3930 \approx 0.949 = 94.9\%$
5. (e) Critical-load peak: fridge (150 W) + 2 LED tubes ($2 \times 18 = 36$ W) = 186 W

The lab uses about 21.52 kWh a day, with a peak load of 3730 W (demand factor $\approx$ 95%). A critical-load-only backup for the fridge and 2 emergency lights would need only 186 W.

Problem 13 [Challenge] Five houses share one small power line. Each house has a connected load of 800 W, but the measured peak load of all five houses together is only 2000 W. Find the group's demand factor, and explain in one sentence why it is usually lower for a group of houses than for a single house.

Solution

1. Total connected load: $5 \times 800 \text{ W} = 4000 \text{ W}$
2. Write the equation: $DF = P_{\text{peak}} \div P_{\text{connected}}$
3. Calculate: $DF = 2000 \div 4000 = 0.50 = 50\%$

The group's demand factor is 50%. With more houses sharing a line, it becomes statistically unlikely that everyone's personal peak happens at the same instant, so a group's demand factor is usually lower than any single house's.

CHAPTER ELEVEN

Solar System Types

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What best defines an off-grid solar system?

- A. A system not connected to the public grid, usually with a battery bank
- B. A system connected to the grid that never uses a battery
- C. Any solar system installed on a rooftop

Answer: A system not connected to the public grid, usually with a battery bank. Off-grid means no connection to the public grid at all. Because there is no grid to help at night, an off-grid system almost always includes a battery bank.

Q2. In a typical off-grid system, what is the correct order of energy flow from the sun to a lamp?

- A. Array → Battery → Charge controller → Inverter → Lamp
- B. Array → Charge controller → Battery → Inverter → Lamp
- C. Array → Inverter → Battery → Charge controller → Lamp

Answer: Array → Charge controller → Battery → Inverter → Lamp. The charge controller sits between the array and the battery, managing safe charging. Only after energy is in the battery does the inverter change it to AC for the lamp.

Q3. A basic on-grid (grid-tied) solar system will keep powering your home during a public grid power cut.

Answer: False. A basic on-grid system has no battery. Its grid-tie inverter switches off automatically during a power cut — this is called anti-islanding — so it gives no backup power at all.

Q4. What is the safety reason a grid-tie inverter switches off during a power cut?

- A. To save the battery from overcharging
- B. To protect workers who may be repairing the grid lines (anti-islanding)
- C. Because the solar panels stop working in a power cut

Answer: To protect workers who may be repairing the grid lines (anti-islanding). This safety feature is called anti-islanding. If the inverter kept feeding the grid line, it could injure repair workers who expect the line to be dead.

Q5. Which of these are normally part of a well-designed hybrid system? (Choose all correct answers.)

- A. A solar array
- B. A battery
- C. A hybrid inverter-charger
- D. The grid and a generator wired together directly, with no changeover switch

Answer: A solar array; A battery; A hybrid inverter-charger. A hybrid system needs an array, a battery, and a hybrid inverter-charger to manage all the sources. The grid and a generator must NEVER be wired together directly — a changeover switch must always allow only one source at a time.

Q6. An off-grid array produces 4.0 kWh in a day. The home uses 1.5 kWh directly during sunny hours. Ignoring losses, how much energy (in kWh) is available to charge the battery?

Answer: 2.5 kWh (± 0.05). $E_{\text{battery}} = E_{\text{array}} - E_{\text{day}} = 4.0 - 1.5 = 2.5 \text{ kWh}$.

Q7. A home's grid is very reliable (outages under 1 hour a week). The owner wants to reduce the electricity bill and does not want to spend money on a battery. What is the best choice?

- A. Off-grid
- B. On-grid (grid-tied)
- C. Hybrid

Answer: On-grid (grid-tied). *With a reliable grid and no interest in backup power, an on-grid (grid-tied) system gives the biggest bill savings for the lowest cost, since no battery is needed.*

Q8. A family has about 8 hours of grid outage every day and already pays for a neighborhood generator subscription. Which system type most directly reduces their generator running hours while still keeping essential loads on during outages?

- A. On-grid only
- B. Off-grid only
- C. Hybrid (solar + battery + grid/generator)

Answer: Hybrid (solar + battery + grid/generator). *A hybrid system uses solar and battery first, only calling on the generator when needed — this cuts generator hours a lot while still giving backup power during the daily outage.*

Q9. In a hybrid system, solar energy is normally used to power the home's loads first, and only the extra (surplus) energy charges the battery.

Answer: True. *This priority order is what makes hybrid systems save money: solar is used directly first, any extra tops up the battery, and only after that does the system draw from the grid or generator.*

Q10. A hybrid system reserves battery energy for critical loads averaging 0.4 kW. The family wants 5 hours of backup. How much usable battery energy (in kWh) do they need?

Answer: 2 kWh (± 0.05). $E_{usable} = t_{backup} \times P_{critical} = 5 \text{ h} \times 0.4 \text{ kW} = 2.0 \text{ kWh}.$

Q11. What device makes sure the grid and a generator are never connected to a building's wiring at the same time?

- A. A charge controller
- B. A changeover (transfer) switch
- C. A battery

Answer: A changeover (transfer) switch. *A changeover switch (transfer switch) connects only one source at a time. Connecting the grid and a generator together at the same time is dangerous.*

Q12. Which of these situations usually point toward choosing a HYBRID system rather than plain on-grid or plain off-grid? (Choose all correct answers.)

- A. The public grid exists but has several hours of outage every day
- B. The public grid is present and almost never fails
- C. There is no public grid anywhere near the site
- D. The family wants some backup power for the fridge and lights during outages

Answer: The public grid exists but has several hours of outage every day; The family wants some backup power for the fridge and lights during outages. *A grid that exists but has daily outages, plus a wish for backup power, both point to hybrid. An always-reliable grid points to on-grid; no grid at all points to off-grid.*

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A family farm is 15 km from the nearest grid line. Bringing a grid connection would cost far more than a solar system. Which system type must they use, and why?

Solution

1. There is no grid connection available at the site, now or affordably in the future.
2. On-grid needs a grid connection, and hybrid normally also uses a grid connection — neither is possible here.
3. Off-grid is designed to work completely independently, producing and storing all its own energy.

The farm must use an off-grid system, because on-grid and grid-connected hybrid systems both need a grid connection that does not exist here.

Problem 2 [Basic] A home has a very reliable grid connection (rare, short outages). The owner wants to lower the electricity bill but does not want to pay for a battery. Which system type fits best, and why?

Solution

1. The owner's main goal is saving money on the bill, not backup power.
2. The grid is reliable, so the lack of backup power in a basic on-grid system is not a big problem here.
3. Off-grid and hybrid both need a battery, which costs more and is not wanted.

On-grid (grid-tied) fits best: it is the lowest-cost way to cut the bill, and a battery is not needed because outages are rare.

Problem 3 [Basic] True or false, with a reason: 'An on-grid solar system will power your refrigerator during a public grid blackout.'

Solution

1. A basic on-grid (grid-tied) system has no battery.
2. Its grid-tie inverter automatically switches off the moment the grid goes down. This safety feature is called anti-islanding, and it protects repair workers.

False. Even in bright sunshine, a basic on-grid system gives no power to the fridge during a blackout, because the inverter shuts itself off.

Problem 4 [Basic] An off-grid array produces 3.0 kWh on a sunny day. The home uses 1.0 kWh of that directly while the sun shines. Ignoring losses, how much energy charges the battery?

Solution

1. Write the equation: $E_{\text{array}} = E_{\text{day}} + E_{\text{battery}}$
 2. Rearrange: $E_{\text{battery}} = E_{\text{array}} - E_{\text{day}} = 3.0 - 1.0$
 3. Calculate: $E_{\text{battery}} = 2.0 \text{ kWh}$
- 2.0 kWh of solar energy is left to charge the battery.**

Problem 5 [Standard] A shop in a town center has about 4 hours of grid outage a day, mostly in the afternoon. The owner already has a small backup generator. Should the owner choose off-grid, on-grid, or hybrid? Give at least two reasons.

Solution

1. The grid exists and works most of the day, so full off-grid independence is not necessary and would cost more than needed.
2. A basic on-grid system would give no power during the daily 4-hour outage, which likely matters during business hours.
3. A hybrid system uses solar and battery to power the shop during the day AND through the outage, and can still fall back on the existing generator if needed.

Hybrid is the best fit: it saves money like an on-grid system while also covering the daily 4-hour outage, working alongside the generator the owner already has.

Problem 6 [Standard] A family pays for a 5-ampere neighborhood generator subscription (see Chapter 1) and wants their lights and refrigerator to keep working no matter what, at the lowest extra cost. Which system type should they choose? Describe how the grid, the generator, and solar would work together across a normal day.

Solution

1. The requirement 'must always work' means a battery is essential, so on-grid alone is ruled out.
2. The family already has a grid connection and a generator, so replacing both with pure off-grid would waste money and remove useful backup options.
3. A hybrid system fits: during the day, solar covers the loads and charges the battery; when the grid goes down in the evening, the hybrid inverter switches to the battery automatically; if the battery runs low before the grid returns, the system can call on the generator.

Hybrid is the best choice. On a normal day: solar and grid share the daytime load and charge the battery; during the evening outage the battery takes over automatically; the generator stays as a last-resort backup, used far less than before.

Problem 7 [Standard] An on-grid home's system produces 5.0 kWh on a sunny weekday when nobody is home for most of the day, so the load is only 1.5 kWh. Using the energy balance from this chapter, find the self-used solar energy, the import, and the export.

Solution

1. The home can only self-consume as much solar as its load needs: self-used = 1.5 kWh (equal to the load).
2. Since solar alone already covers the whole load, no grid import is needed: $E_{\text{import}} = 0$
3. Use the balance equation: $E_{\text{solar}} + E_{\text{import}} = E_{\text{load}} + E_{\text{export}} \rightarrow 5.0 + 0 = 1.5 + E_{\text{export}}$
4. Solve: $E_{\text{export}} = 5.0 - 1.5 = 3.5 \text{ kWh}$

The home self-consumes 1.5 kWh, imports 0 kWh, and exports 3.5 kWh of surplus solar energy.

Problem 8 [Standard] A health center wants at least 6 hours of hybrid battery backup for its critical loads (Chapter 10), which average 0.5 kW. How much usable battery energy must the system reserve for backup?

Solution

1. Write the equation: $t_{\text{backup}} = E_{\text{usable}} \div P_{\text{critical}}$
2. Rearrange: $E_{\text{usable}} = t_{\text{backup}} \times P_{\text{critical}}$
3. Put in the numbers: $E_{\text{usable}} = 6 \text{ h} \times 0.5 \text{ kW}$
4. Calculate: $E_{\text{usable}} = 3.0 \text{ kWh}$

The system must reserve at least 3.0 kWh of usable battery energy for the health center's 6-hour backup.

Problem 9 [Standard] List two advantages and two disadvantages of a hybrid system compared with a plain off-grid system, for a home that DOES have a grid connection.

Solution

1. Advantage 1: because the grid can help, the battery and array can be smaller (and cheaper) than a pure off-grid system sized to cover 100% of the load alone.
2. Advantage 2: a hybrid system can actively save money every day (solar offsets grid import), while a pure off-grid system just meets its own needs with no bill to compare against.
3. Disadvantage 1: a hybrid inverter-charger and its settings are more complex, with more that can go wrong, than a simple off-grid system.
4. Disadvantage 2: a hybrid system still depends partly on the grid or a generator; unlike a well-sized off-grid system built for total independence, it is not designed to survive a very long combined failure of grid, generator, and sun.

Hybrid systems usually cost less and actively cut bills, but they are more complex and are not built for complete independence the way an off-grid system is.

Problem 10 [Standard] A solar streetlight on a remote road has no grid connection nearby. It must light up automatically for about 10 hours every night, all year, including cloudy weeks. Which system type fits, and what part of the design needs the most careful attention so the light never goes dark?

Solution

1. There is no grid at the site, so on-grid and grid-connected hybrid are not possible — the streetlight must be off-grid.
2. The light must run every single night, including after cloudy days, so the battery cannot just cover one average night — it needs extra capacity (days of autonomy) for a run of poor sunshine.
3. The array and charge controller must also be sized to fully recharge the battery even on a below-average day, not just a perfect sunny day.

The streetlight must be off-grid. The battery's autonomy — its ability to survive several cloudy days in a row — is the part that needs the most careful design attention. Chapter 12 covers this sizing method in full.

Problem 11 [Challenge] A remote village has no grid connection at all. A diesel generator currently runs the village mill for a few hours each evening. Decide the best system type for each of these, with a reason: (a) individual homes, needed mainly for lighting and phone charging; (b) the village mill, which needs a large, steady amount of power only in the evening.

Solution

1. Neither situation has access to a public grid, so a plain on-grid or a grid-connected hybrid system is impossible in either case.
2. (a) Individual homes have small, steady loads (lights, phone charging) that fit well within a small off-grid solar-plus-battery system, with no need to run a noisy, costly generator just for this.
3. (b) The mill needs a large amount of power for a short evening period. A large array and battery could do the whole job, but if the load is very high, it may be more practical to size solar and battery to cover part of

the load and let the existing generator top up the rest — still an off-grid arrangement, because there is no public grid to tie into.

Homes: small off-grid solar-plus-battery systems can replace the generator for daily use. The mill: either a larger off-grid system, or an off-grid system combined with the existing generator as a backup/top-up source — never on-grid or grid-tied hybrid, since no grid is present.

Problem 12 [Challenge] A family's daily grid outage is 8 hours, usually in the evening. Their critical loads average 0.4 kW. Their installer offers two battery options: Option A stores 2.4 kWh usable, Option B stores 4.0 kWh usable. (a) Find the backup hours for each option. (b) Which option comfortably covers the daily outage? (c) Why might the family still choose to keep their generator connection, even with the better battery option?

Solution

1. (a) Option A: $t_{\text{backup}} = E_{\text{usable}} \div P_{\text{critical}} = 2.4 \div 0.4 = 6$ hours
2. (a) Option B: $t_{\text{backup}} = 4.0 \div 0.4 = 10$ hours
3. (b) The daily outage is 8 hours. Option A (6 h) falls short; Option B (10 h) comfortably covers it.
4. (c) Even with Option B, a run of cloudy days (less solar to recharge the battery), an unusually long outage, or extra loads being used could still need more than 10 hours of stored energy, so keeping the generator as a last resort adds an extra layer of safety.

Option A gives 6 hours of backup (not enough for the 8-hour outage); Option B gives 10 hours (enough). The family may still keep the generator for the rare times the outage is longer than normal or the weather has been cloudy.

Problem 13 [Challenge] A university building has a reliable grid connection (rare outages) and wants to demonstrate solar technology to students while cutting its electricity bill. The budget is limited, and the maintenance team does not want to deal with battery upkeep. Which system type fits best, and what is the main energy-flow risk they must accept?

Solution

1. A limited budget and no wish for battery maintenance both point away from off-grid and hybrid, since both need a battery bank.
2. A reliable grid means the main downside of on-grid — no backup during outages — will rarely be a problem in practice.
3. The main energy-flow risk to accept: because there is no battery, the grid-tie inverter will switch off (anti-islanding) during any power cut, however rare, giving zero solar power at exactly the moment the building might want it most.

On-grid (grid-tied) is the best fit for cost and simplicity. The building must accept that, during any grid outage, the solar system will also go dark — it gives bill savings, not backup power.

Problem 14 [Challenge] Before installing hybrid solar, a family ran their neighborhood generator 8 hours a day, at a subscription cost of 50,000 IQD per month (example numbers, as in Chapter 1). After installing a hybrid system, solar and battery cover all but 2 hours of generator use each day. Assuming the generator's cost scales roughly with the hours used: (a) What is the new daily generator running time? (b) What is the new monthly generator cost? (c) How much do they save per month on the generator alone?

Solution

1. (a) The new daily generator running time is given: 2 hours a day, down from 8 hours.
2. (b) Find the cost per hour: $50,000 \text{ IQD} \div (8 \text{ h/day} \times 30 \text{ days}) = 50,000 \div 240 \approx 208.3 \text{ IQD per generator-hour}$
3. (b) New monthly cost: $2 \text{ h/day} \times 30 \text{ days} \times 208.3 \text{ IQD/h} \approx 12,500 \text{ IQD}$
4. (c) Savings: $50,000 - 12,500 = 37,500 \text{ IQD per month}$

Cutting generator use from 8 to 2 hours a day saves the family about 37,500 IQD a month in this example — showing why hybrid solar is so attractive alongside a generator subscription.

CHAPTER TWELVE

Off-Grid System Design

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. Which list shows the off-grid design chain in the correct order?

- A. Energy demand → sun data → array → battery bank → controller → inverter → cables
- B. Inverter → controller → battery bank → array → cables → sun data → energy demand
- C. Battery bank → array → energy demand → inverter → controller → cables → sun data

Answer: Energy demand → sun data → array → battery bank → controller → inverter → cables. Each step needs the answer from the step before it: you must know the energy demand before sizing the array, the array before the battery bank, and so on, ending with cables and protection.

Q2. A 24 V-rated inverter, a 12 V battery bank, and a 48 V-rated controller output can all be safely connected in the same off-grid system, as long as the total power roughly matches.

Answer: False. Every DC-side component — battery bank, controller output, and inverter input — must share the SAME system voltage. Matching power alone is not enough; mismatched voltages can destroy equipment and are a fire risk.

Q3. A home needs 3.6 kWh per day. The design month gives 4.0 peak sun hours, and the performance ratio is 0.80. Find the minimum array size, in kW.

Answer: 1.125 kW (± 0.02). $P_{array} = E_{daily} \div (PSH \times PR) = 3.6 \div (4.0 \times 0.80) = 3.6 \div 3.2 = 1.125 \text{ kW}$.

Q4. An off-grid array for a home with a fairly constant year-round load should normally be sized using the year's BEST (sunniest) month, to save money on panels.

Answer: False. It should be sized using the WORST month (the design month, usually winter here). An off-grid home has no grid to fall back on, so the array must meet the load even in the hardest month of the year.

Q5. A cabin needs 2400 Wh per day from its battery bank. It is designed for 2 days of autonomy, a 24 V system, and batteries with a maximum depth of discharge of 0.5. Find the required battery bank capacity, in Ah.

Answer: 400 Ah (± 5). $C_{bank} = (E_{daily} \times N_{auto}) \div (V_{sys} \times DoD) = (2400 \times 2) \div (24 \times 0.5) = 4800 \div 12 = 400 \text{ Ah}$.

Q6. In an off-grid design, '2 days of autonomy' means:

- A. The battery bank alone can supply the home's full daily need for two days, with little or no help from the sun
- B. The solar panels take two days to fully charge an empty battery bank
- C. The equipment comes with a two-day manufacturer's warranty

Answer: The battery bank alone can supply the home's full daily need for two days, with little or no help from the sun. Days of autonomy is how many days the battery bank must carry the whole load by itself — for example, during a run of cloudy days.

Q7. Which checks should be made before choosing a charge controller for an MPPT system? (Choose all correct answers.)

- A. The array's short-circuit current (I_{sc}) × a safety factor
- B. The array's open-circuit voltage (V_{oc}) stays under the controller's rated input voltage
- C. The current reaching the battery, estimated from the array's rated power ÷ system voltage

D. The physical color of the controller's plastic case

Answer: The array's short-circuit current (I_{sc}) $\times$ a safety factor; The array's open-circuit voltage (V_{oc}) stays under the controller's rated input voltage; The current reaching the battery, estimated from the array's rated power $\div$ system voltage. A complete controller check covers the array-side current ($I_{sc} \times 1.25$), the array-side voltage limit (V_{oc}), and a battery-side power check — especially important when the array's voltage is much higher than the battery's. The case color has no electrical meaning.

Q8. Loads running together in the evening total 340 W of continuous power. Using a 25% safety margin, find the minimum continuous inverter rating, in W.

Answer: 425 W (± 5). $P_{cont} = P_{total} \times (1 + m) = 340 \times 1.25 = 425 \text{ W}$.

Q9. What does a performance ratio (PR) of 0.80 mean for a solar array?

- A. The system delivers about 80% of the array's ideal output, once real losses are included
- B. The battery bank is charged to 80% of its capacity
- C. The array is tilted at an 80-degree angle

Answer: The system delivers about 80% of the array's ideal output, once real losses are included. Performance ratio compares real output with ideal output. A PR of 0.80 means real losses (heat, dust, wiring, equipment) take about 20% away from the ideal figure.

Q10. A system has these example derating factors: temperature 0.90, dust 0.95, and wiring 0.98. Ignoring controller and inverter losses, find the combined derating factor from these three, as a percentage.

Answer: 83.8 % (± 1). Multiply the factors: $0.90 \times 0.95 \times 0.98 = 0.8379$, which is about 83.8%. Derating factors are always multiplied together, never added.

Q11. In a complete off-grid design, the battery bank, the charge controller's battery-side output, and the inverter's DC input must all be built for the same system voltage.

Answer: True. This is one of the chapter's central checks. Every DC connection point in the chain — battery, controller output, and inverter input — must share one system voltage, commonly 12 V, 24 V, or 48 V.

Q12. A home needs 2.6 kWh per day. In the design month, its site gets 3.0 peak sun hours, and the design uses a performance ratio of 0.80. Which array size is closest to the true minimum requirement?

- A. About 1.08 kW
- B. About 2.6 kW
- C. About 0.5 kW

Answer: About 1.08 kW. $P_{array} = E_{daily} \div (PSH \times PR) = 2.6 \div (3.0 \times 0.80) = 2.6 \div 2.4 \approx 1.08 \text{ kW}$ — matching Lesson 6's complete worked design.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A cabin needs 2000 Wh per day. The design month gives 5.0 peak sun hours. Using a performance ratio of 0.80, find the minimum array size, in W.

Solution

1. Write the equation: $P_{array} = E_{daily} \div (PSH \times PR)$
2. Put in the numbers: $P_{array} = 2000 \text{ Wh} \div (5.0 \text{ h} \times 0.80)$
3. Calculate the bottom: $5.0 \times 0.80 = 4.0$
4. Divide: $P_{array} = 2000 \div 4.0 = 500 \text{ W}$

The minimum array size is 500 W.

Problem 2 [Basic] A small home needs 1800 Wh per day from its battery bank. The design uses 1 day of autonomy, a 12 V system, and a battery with a maximum depth of discharge of 0.5. Find the required battery bank capacity, in Ah.

Solution

1. Write the equation: $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (1800 \text{ Wh} \times 1) \div (12 \text{ V} \times 0.5)$
3. Calculate the bottom: $12 \times 0.5 = 6$
4. Divide: $C_{\text{bank}} = 1800 \div 6 = 300 \text{ Ah}$

The required battery bank capacity is 300 Ah.

Problem 3 [Basic] A small array has a short-circuit current (I_{sc}) of 7 A. Using the 1.25 safety factor, find the minimum controller current rating, then choose a standard size from 10, 20, 30, or 40 A.

Solution

1. Write the equation: $I_{\text{controller}} \geq I_{\text{SC}} \times 1.25$
2. Put in the numbers: $I_{\text{controller}} \geq 7 \text{ A} \times 1.25$
3. Calculate: $I_{\text{controller}} \geq 8.75 \text{ A}$
4. Round UP to the next standard size: choose a 10 A controller

The controller must be rated at least 8.75 A; a standard 10 A controller is the right choice.

Problem 4 [Basic] Loads running together total 220 W of continuous power. Using a 25% safety margin, find the minimum continuous inverter rating, then choose a standard size from 300, 500, or 1000 W.

Solution

1. Write the equation: $P_{\text{cont}} \geq P_{\text{total}} \times (1 + m)$
2. Put in the numbers: $P_{\text{cont}} \geq 220 \text{ W} \times (1 + 0.25) = 220 \times 1.25$
3. Calculate: $P_{\text{cont}} \geq 275 \text{ W}$
4. Round up to the next standard size: choose a 300 W continuous inverter

The inverter must be rated at least 275 W continuous; a standard 300 W inverter is the right choice.

Problem 5 [Standard] A home needs 5500 Wh per day. Its design month gives 3.5 peak sun hours, and the performance ratio is 0.75. Find the minimum array size in W, then choose a number of 330 W panels.

Solution

1. Write the equation: $P_{\text{array}} = E_{\text{daily}} \div (\text{PSH} \times \text{PR})$
2. Put in the numbers: $P_{\text{array}} = 5500 \div (3.5 \times 0.75)$
3. Calculate the bottom: $3.5 \times 0.75 = 2.625$
4. Divide: $P_{\text{array}} = 5500 \div 2.625 \approx 2095.2 \text{ W}$
5. Choose panels: $2095.2 \div 330 \approx 6.35 \rightarrow \text{round up to 7 panels} = 2310 \text{ W}$

At least 2095.2 W is needed; seven 330 W panels (2310 W) is a practical, buildable choice.

Problem 6 [Standard] A home needs 4000 Wh per day from its battery bank, with 3 days of autonomy, a 24 V system, and AGM batteries with a maximum DoD of 0.6. Find the required capacity in Ah, and the number of 12 V, 100 Ah batteries needed (series and parallel).

Solution

1. Write the equation: $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (4000 \times 3) \div (24 \times 0.6)$
3. Calculate the top: $4000 \times 3 = 12,000 \text{ Wh}$
4. Calculate the bottom: $24 \times 0.6 = 14.4$
5. Divide: $C_{\text{bank}} = 12,000 \div 14.4 \approx 833.3 \text{ Ah}$
6. Batteries in series for 24 V: $24 \div 12 = 2$ per string
7. Strings in parallel for capacity: $833.3 \div 100 \approx 8.3 \rightarrow$ round up to 9 strings
8. Total batteries: $2 \times 9 = 18$, giving an actual 900 Ah

At least 833.3 Ah is needed; 18 batteries (2 series $\times$ 9 parallel) of 12 V, 100 Ah give an actual 900 Ah.

Problem 7 [Standard] An array of 8 panels, each $V_{\text{oc}} = 32 \text{ V}$, $I_{\text{sc}} = 9 \text{ A}$, $V_{\text{mp}} = 27 \text{ V}$, $I_{\text{mp}} = 8.5 \text{ A}$, is wired as two panels in series with four such strings in parallel (2S4P), feeding a 24 V battery bank through an MPPT controller. Find the minimum controller current using both the short-circuit current rule and the power check, and state which one governs.

Solution

1. String I_{sc} (series does not add current): 9 A. Array I_{sc} (4 strings in parallel): $4 \times 9 = 36 \text{ A}$
2. Check 1 — current rule: $I_{\text{controller}} \geq 36 \times 1.25 = 45 \text{ A} \rightarrow$ round up to 50 A
3. Array V_{mp} (2 in series): $2 \times 27 = 54 \text{ V}$. Array I_{mp} (4 in parallel): $4 \times 8.5 = 34 \text{ A}$. Array power: $54 \times 34 = 1836 \text{ W}$
4. Check 2 — power check at 24 V: $I_{\text{battery}} \approx 1836 \div 24 = 76.5 \text{ A} \rightarrow$ round up to 80 A
5. Compare: Check 2 (80 A) is larger than Check 1 (50 A), so Check 2 governs

Choose an 80 A MPPT controller. The power check governs here because the array's operating voltage (54 V) is much higher than the 24 V battery voltage.

Problem 8 [Standard] A borehole pump motor runs at 550 W, with a starting surge of about 4 times its running power. Other loads running at the same moment total 150 W. Find (a) the minimum surge inverter rating and (b) the minimum continuous inverter rating with a 25% margin, then choose a standard inverter size from the pairs 1000/2000 W or 1500/3000 W.

Solution

1. Pump surge: $550 \times 4 = 2200 \text{ W}$
2. (a) Minimum surge rating: $150 + 2200 = 2350 \text{ W}$
3. Continuous total: $550 + 150 = 700 \text{ W}$
4. (b) With a 25% margin: $700 \times 1.25 = 875 \text{ W}$
5. Check a 1000 W / 2000 W inverter: continuous $1000 \geq 875 \checkmark$, but surge $2000 < 2350 \text{ X}$ — too small
6. Check the next size, 1500 W / 3000 W: continuous $1500 \geq 875 \checkmark$, surge $3000 \geq 2350 \checkmark$

The surge requirement (2350 W) forces a 1500 W continuous / 3000 W surge inverter, even though the continuous requirement alone (875 W) looked much smaller.

Problem 9 [Standard] A system has these example derating factors: temperature 0.92, dust 0.93, wiring 0.98, controller 0.96, and inverter 0.95. (a) Find the overall performance ratio. (b) Using this PR, find the daily energy produced by a 2.5 kWp array at 5.0 peak sun hours.

Solution

1. (a) Multiply all five factors, one at a time: $0.92 \times 0.93 = 0.8556$
2. $0.8556 \times 0.98 = 0.8385$
3. $0.8385 \times 0.96 = 0.8049$
4. $0.8049 \times 0.95 \approx 0.7647 \rightarrow \text{PR} \approx 0.76 \text{ (76\%)}$
5. (b) Write the equation: $E_{\text{array}} = P_{\text{array}} \times \text{PSH} \times \text{PR}$
6. Put in the numbers: $E_{\text{array}} = 2.5 \text{ kW} \times 5.0 \text{ h} \times 0.7647 \approx 9.56 \text{ kWh}$

The overall performance ratio is about 0.76, and the array would produce about 9.56 kWh on a day with 5.0 peak sun hours.

Problem 10 [Challenge] A small off-grid shop in Sulaymaniyah has these daily loads: 10 LED lights (12 W each, 6 h/day), one drinks refrigerator (140 W, 10 h/day effective), one ceiling fan (65 W, 8 h/day), and one computer (90 W, 6 h/day). The design month gives 3.2 peak sun hours, with a performance ratio of 0.80. The shop wants 1 day of autonomy at a 24 V system voltage, using AGM batteries with DoD = 0.6. Panels are 350 W each; batteries are 12 V, 150 Ah. Find: (a) the daily energy need; (b) the array size and panel count; (c) the battery bank capacity and battery count; (d) the inverter's minimum continuous rating (25% margin) and surge rating (the fridge's surge is about 4×, and all other loads may already be running when it starts).

Solution

1. (a) Lights: $10 \times 12 \times 6 = 720 \text{ Wh}$. Fridge: $140 \times 10 = 1400 \text{ Wh}$. Fan: $65 \times 8 = 520 \text{ Wh}$. Computer: $90 \times 6 = 540 \text{ Wh}$. Total: $720+1400+520+540 = 3180 \text{ Wh}$
2. (b) $P_{\text{array}} = E_{\text{daily}} \div (\text{PSH} \times \text{PR}) = 3180 \div (3.2 \times 0.80) = 3180 \div 2.56 \approx 1242.2 \text{ W}$. Panels: $1242.2 \div 350 \approx 3.55 \rightarrow$ round up to 4 panels = 1400 W
3. (c) $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD}) = (3180 \times 1) \div (24 \times 0.6) = 3180 \div 14.4 \approx 220.8 \text{ Ah}$. Series: $24 \div 12 = 2$. Parallel: $220.8 \div 150 \approx 1.47 \rightarrow$ round up to 2 strings. Total batteries: $2 \times 2 = 4$, actual 300 Ah
4. (d) Continuous: $(10 \times 12) + 140 + 65 + 90 = 120+140+65+90 = 415 \text{ W}$. With a 25% margin: $415 \times 1.25 = 518.75 \text{ W} \rightarrow 500 \text{ W}$ is not enough, so round up to 1000 W
5. Fridge surge: $140 \times 4 = 560 \text{ W}$. Other loads: $415 - 140 = 275 \text{ W}$. Surge total: $275 + 560 = 835 \text{ W}$
6. Check a 1000 W / 2000 W inverter: continuous $1000 \geq 518.75 \checkmark$; surge $2000 \geq 835 \checkmark$

Daily need 3180 Wh; array = 4 × 350 W panels (1400 W); battery bank = 4 × 12 V, 150 Ah batteries (2S2P, 300 Ah actual); inverter = 1000 W continuous / 2000 W surge — all built to the same 24 V system voltage.

Problem 11 [Challenge] A rural one-room classroom, fully off-grid, has these daily loads: 8 LED lights (10 W each, 5 h/day), a laptop-charging station (60 W, 4 h/day), a small printer (80 W, 1 h/day), and a fan (70 W, 5 h/day). The design month gives 3.5 peak sun hours, with a performance ratio of 0.78. The school accepts 1 day of autonomy at a 12 V system voltage, using lead-acid batteries with DoD = 0.5. Panels are 300 W each; batteries are 12 V, 100 Ah. Find: (a) the daily energy need; (b) the array size and panel count; (c) the battery bank capacity and battery count; (d) the inverter's minimum continuous rating (use a 20% margin this time) and surge rating (the fan's surge is about 2×).

Solution

1. (a) Lights: $8 \times 10 \times 5 = 400$ Wh. Laptop: $60 \times 4 = 240$ Wh. Printer: $80 \times 1 = 80$ Wh. Fan: $70 \times 5 = 350$ Wh. Total: $400+240+80+350 = 1070$ Wh

2. (b) $P_{\text{array}} = 1070 \div (3.5 \times 0.78) = 1070 \div 2.73 \approx 391.9$ W. Panels: $391.9 \div 300 \approx 1.31 \rightarrow$ round up to 2 panels = 600 W

3. (c) $C_{\text{bank}} = (1070 \times 1) \div (12 \times 0.5) = 1070 \div 6 \approx 178.3$ Ah. Series: $12 \div 12 = 1$ (already at 12 V). Parallel: $178.3 \div 100 \approx 1.78 \rightarrow$ round up to 2 strings, actual 200 Ah

4. (d) Continuous: $(8 \times 10) + 60 + 80 + 70 = 80+60+80+70 = 290$ W. With a 20% margin: $290 \times 1.20 = 348$ W $\rightarrow$ round up to 500 W

5. Fan surge: $70 \times 2 = 140$ W. Other loads: $290 - 70 = 220$ W. Surge total: $220 + 140 = 360$ W

6. Check a 500 W / 1000 W inverter: continuous $500 \geq 348$ ✓; surge $1000 \geq 360$ ✓

Daily need 1070 Wh; array = 2 × 300 W panels (600 W); battery bank = 2 × 12 V, 100 Ah batteries in parallel (200 Ah actual); inverter = 500 W continuous / 1000 W surge, all at 12 V. Notice that here the CONTINUOUS check governs, not the surge — the fan's surge factor is small.

Problem 12 [Challenge] A solar LED streetlight in a remote area runs at 50 W for 10 hours every night, with no daytime load. It uses two 150 W panels (each $V_{oc} = 22$ V, $I_{sc} = 8.6$ A) wired in parallel, matched to a 12 V nominal battery through a PWM controller. The design uses 3 days of autonomy (a hard-to-reach site), a single 12 V LiFePO4 battery with DoD = 0.8, a design-month PSH of 3.0 h/day, and PR = 0.75. Find: (a) the daily energy need; (b) the minimum array size, and whether the two 150 W panels are enough; (c) the required battery capacity, and whether a single 12 V, 200 Ah LiFePO4 battery is enough; (d) the minimum controller current and a standard size. Also explain why this system needs no inverter.

Solution

1. (a) $E_{\text{daily}} = 50 \text{ W} \times 10 \text{ h} = 500$ Wh

2. (b) $P_{\text{array}} = E_{\text{daily}} \div (\text{PSH} \times \text{PR}) = 500 \div (3.0 \times 0.75) = 500 \div 2.25 \approx 222.2$ W. The two 150 W panels give 300 W, which is more than 222.2 W — enough

3. (c) $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD}) = (500 \times 3) \div (12 \times 0.8) = 1500 \div 9.6 \approx 156.25$ Ah. A single 12 V, 200 Ah battery gives more than 156.25 Ah — enough, with no series or parallel wiring needed

4. (d) Array I_{sc} (2 panels in parallel): $2 \times 8.6 = 17.2$ A. Controller minimum: $17.2 \times 1.25 = 21.5$ A $\rightarrow$ round up to a 30 A controller. Because both panels are 12 V-nominal, matching the 12 V battery, a PWM controller is a good, low-cost fit (Chapter 7) — no need for MPPT here

5. No inverter is needed because an LED streetlight runs directly on DC power. There is no AC appliance in this system, so there is nothing for an inverter to supply

Daily need 500 Wh; two 150 W panels (300 W) and one 12 V, 200 Ah LiFePO4 battery are both comfortably enough; a 30 A PWM controller completes the system, with no inverter required.

CHAPTER THIRTEEN

On-Grid and Hybrid System Design

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. An off-grid array (Chapter 12) is sized using the design month's peak sun hours. Why is a GRID-TIED array normally sized using the ANNUAL AVERAGE peak sun hours instead?

- A. Because the grid can instantly supply any shortfall in a weak month, so the array does not need to survive the worst month alone
- B. Because the annual average is always a bigger number than the design month value, giving a cheaper design
- C. Because grid-tied panels physically produce more power than off-grid panels

Answer: Because the grid can instantly supply any shortfall in a weak month, so the array does not need to survive the worst month alone. An off-grid system has no backup, so it must be sized for its worst month. A grid-tied system always has the grid available to fill any gap, so designers use the annual average to size for a sensible yearly offset instead of the hardest month.

Q2. A home uses 8 kWh per day on average (annual average). The site's annual average peak sun hours are 5.0 h/day, and the performance ratio is 0.80. Find the minimum array size for a 50% offset, in kW.

Answer: 1 kW (± 0.05). $P_{array} = (\text{Offset} \times E_{daily}) \div (\text{PSH}_{avg} \times \text{PR}) = (0.5 \times 8000 \text{ Wh}) \div (5.0 \times 0.80) = 4000 \div 4.0 = 1000 \text{ W} = 1.0 \text{ kW}.$

Q3. Net metering rules, such as the credit rate for exported energy, are the same in every country and never change over time.

Answer: False. Net metering and net billing rules are set locally, by country, state, or utility, and they can change as policy changes. Always confirm the current rule with the local electricity provider before relying on it in a design.

Q4. Under TRUE net metering, where exported and imported energy are credited at the SAME rate, what mainly decides a customer's bill over a billing period?

- A. Only the total energy imported minus the total energy exported over the period
- B. The exact clock time each kilowatt-hour was used during the day
- C. The brand of the grid-tie inverter

Answer: Only the total energy imported minus the total energy exported over the period. When import and export share one rate, the timing of self-consumption versus export does not change the bill — only the TOTAL net energy, import minus export, over the period matters.

Q5. A home imports 10 kWh and exports 4 kWh in one day. Import costs an example 100 IQD/kWh; because this utility uses net billing, export is credited at only 50 IQD/kWh. Find the day's bill, in IQD.

Answer: 800 IQD (± 10). $\text{Bill} = (\text{Import} \times \text{import tariff}) - (\text{Export} \times \text{export tariff}) = (10 \times 100) - (4 \times 50) = 1000 - 200 = 800 \text{ IQD}.$

Q6. Which of these are good reasons a hybrid system's generator might still be needed sometimes? (Choose all correct answers.)

- A. A run of cloudy days longer than the battery and array were sized for
- B. An unusually high-use evening that leaves the battery only partly recharged the next day
- C. The solar array being deliberately sized smaller than the full daily need, to control cost

D. Solar panels being more expensive to buy when they are new

Answer: A run of cloudy days longer than the battery and array were sized for; An unusually high-use evening that leaves the battery only partly recharged the next day; The solar array being deliberately sized smaller than the full daily need, to control cost. *Cloudy runs beyond the design, an unusually heavy evening, or a smaller-than-full array chosen to save money can all mean the battery cannot cover every evening alone — the generator exists exactly for these moments. The purchase price of panels has nothing to do with when the generator is needed.*

Q7. In a hybrid system's normal source priority, the generator is usually the LAST source used, after solar, battery, and grid have all been considered.

Answer: True. *Solar is free once installed, so it is used first. The battery is used next because its stored energy is normally cheaper than fuel. The grid, when available, is normally cheaper than running a generator. The generator, using paid fuel, is normally the last resort.*

Q8. A hybrid system's critical loads total 200 W. The typical daily grid outage is 5 hours. The system uses a 24 V system voltage and batteries with a maximum depth of discharge of 0.6. Find the required battery bank capacity, in Ah.

Answer: 69.4 Ah (± 1). $C_{bank} = (P_{critical} \times t_{backup}) \div (V_{sys} \times DoD) = (200\text{ W} \times 5\text{ h}) \div (24\text{ V} \times 0.6) = 1000 \div 14.4 \approx 69.4\text{ Ah}.$

Q9. What is the main idea behind sizing solar and a battery to reduce a hybrid system's generator run hours?

- A. Let solar and the battery cover as much of the daily backup energy as possible, so the generator only supplies what is left over
- B. Turn the generator off completely and never use it, even during long cloudy runs
- C. Run the generator every day at a fixed time so it stays in good condition

Answer: Let solar and the battery cover as much of the daily backup energy as possible, so the generator only supplies what is left over. *The goal is not to remove the generator, but to shrink its job: the bigger the share of backup energy that solar and the battery can supply, the fewer hours the generator needs to run.*

Q10. Before adding a battery, a generator alone had to supply 3000 Wh during an evening outage, running at an average loading of 1500 W. After adding a battery that now supplies 1800 Wh of that same need, how many hours does the generator run?

Answer: 0.8 hours (± 0.05). *Energy still needed from the generator = 3000 – 1800 = 1200 Wh. Generator hours = Energy ÷ Power = 1200 Wh ÷ 1500 W = 0.8 h.*

Q11. In Iraq and the Kurdistan Region today, a single standardized net-metering program is available to every household on identical terms, so no local confirmation is needed.

Answer: False. *Rules for connecting solar to the grid, including any net-metering or net-billing arrangement, can differ between areas and utilities in the region, and are still developing. Many home systems here are designed as off-grid or hybrid instead of relying on grid export. Always confirm the current local rule directly with your electricity provider — this course cannot state one fixed national rule.*

Q12. What does a 'consumption offset' of 70% mean for a grid-tied solar design?

- A. The array is sized to produce about 70% of the home's average energy use over a year
- B. The battery is charged to 70% of its capacity
- C. The home's electricity price is permanently reduced by a fixed 70%

Answer: The array is sized to produce about 70% of the home's average energy use over a year. *Consumption offset is the target share of a home's average annual energy use that the solar array is sized to produce. A 70% offset does not automatically mean a 70% cheaper bill — Lesson 2 shows how the actual billing outcome depends on the metering rules used.*

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A home uses 6 kWh per day on average (annual average). The site's annual average peak sun hours are 5.0 h/day, and the performance ratio is 0.80. Find the minimum array size for a 50% offset, in W.

Solution

1. Write the equation: $P_{\text{array}} = (\text{Offset} \times E_{\text{daily}}) \div (\text{PSH}_{\text{avg}} \times \text{PR})$
2. Put in the numbers: $P_{\text{array}} = (0.5 \times 6000 \text{ Wh}) \div (5.0 \times 0.80)$
3. Calculate the top: $0.5 \times 6000 = 3000 \text{ Wh}$
4. Calculate the bottom: $5.0 \times 0.80 = 4.0$
5. Divide: $P_{\text{array}} = 3000 \div 4.0 = 750 \text{ W}$

The minimum array size for a 50% offset is 750 W.

Problem 2 [Basic] In one month, a home imports 300 kWh from the grid and exports 120 kWh of solar to the grid. Using true net metering (the same rate for import and export) at an example tariff of 100 IQD/kWh, find the month's bill.

Solution

1. Write the equation: $\text{Bill} = (E_{\text{import}} - E_{\text{export}}) \times \text{tariff}$
2. Put in the numbers: $\text{Bill} = (300 - 120) \times 100$
3. Calculate: $\text{Bill} = 180 \times 100 = 18,000 \text{ IQD}$

The month's bill is 18,000 IQD.

Problem 3 [Basic] A hybrid system's critical loads total 250 W. The daily grid outage is 4 hours. The system voltage is 12 V, and the battery's maximum depth of discharge is 0.5. Find the required battery bank capacity, in Ah.

Solution

1. Write the equation: $C_{\text{bank}} = (P_{\text{critical}} \times t_{\text{backup}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (250 \text{ W} \times 4 \text{ h}) \div (12 \text{ V} \times 0.5)$
3. Calculate the top: $250 \times 4 = 1000 \text{ Wh}$
4. Calculate the bottom: $12 \times 0.5 = 6$
5. Divide: $C_{\text{bank}} = 1000 \div 6 \approx 166.7 \text{ Ah}$

The required battery bank capacity is about 166.7 Ah.

Problem 4 [Basic] An evening outage needs 2000 Wh of energy. A battery supplies 800 Wh of this. The generator supplies the rest, running at an average loading of 1000 W. Find the generator run time, in hours and in minutes.

Solution

1. Find the energy still needed: $E_{\text{gen}} = 2000 - 800 = 1200 \text{ Wh}$
2. Write the equation: $t_{\text{gen}} = E_{\text{gen}} \div P_{\text{gen}}$

3. Divide: $t_{\text{gen}} = 1200 \div 1000 = 1.2 \text{ h}$
4. Convert to minutes: $1.2 \times 60 = 72 \text{ minutes}$

The generator must run for 1.2 hours, or 72 minutes.

Problem 5 [Standard] A shop's average daily consumption is 20 kWh. The owner wants a 70% offset. The site's annual average peak sun hours are an example 5.5 h/day, and the performance ratio is 0.78. Find the minimum array size, then choose a number of 450 W panels.

Solution

1. Write the equation: $P_{\text{array}} = (\text{Offset} \times E_{\text{daily}}) \div (\text{PSH}_{\text{avg}} \times \text{PR})$
2. Calculate the top: $0.70 \times 20,000 = 14,000 \text{ Wh}$
3. Calculate the bottom: $5.5 \times 0.78 = 4.29$
4. Divide: $P_{\text{array}} = 14,000 \div 4.29 \approx 3263.4 \text{ W}$
5. Choose panels: $3263.4 \div 450 \approx 7.25 \rightarrow \text{round up to 8 panels} = 3600 \text{ W}$

At least 3263.4 W is needed; eight 450 W panels (3600 W) is a practical, buildable choice.

Problem 6 [Standard] A home's solar system produces 15 kWh on an average day. Of this, 6 kWh is used directly in the home (self-consumption), and the rest is exported. The home's total daily consumption is 18 kWh (it imports the remaining need from the grid beyond its self-consumed solar). Using an example import tariff of 100 IQD/kWh: (a) find the energy exported and imported; (b) find the bill under true net metering; (c) find the bill under net billing, where export is credited at only 60 IQD/kWh.

Solution

1. (a) Exported = production – self-consumed = $15 - 6 = 9 \text{ kWh}$. Imported = total consumption – self-consumed = $18 - 6 = 12 \text{ kWh}$
2. (b) True net metering: Bill = (Import – Export) $\times$ tariff = $(12 - 9) \times 100 = 3 \times 100 = 300 \text{ IQD}$
3. (c) Net billing: Bill = (Import $\times$ import tariff) – (Export $\times$ export tariff) = $(12 \times 100) - (9 \times 60) = 1200 - 540 = 660 \text{ IQD}$

The home exports 9 kWh and imports 12 kWh a day. True net metering gives a 300 IQD bill; net billing, with its lower export rate, gives a higher 660 IQD bill for the same day.

Problem 7 [Standard] A hybrid system's critical loads total 480 W. The typical daily grid outage is 5 hours. The system uses a 48 V system voltage and AGM batteries with a maximum depth of discharge of 0.7. Find the required battery capacity in Ah, and the number of 12 V, 100 Ah batteries needed (series and parallel).

Solution

1. Write the equation: $C_{\text{bank}} = (P_{\text{critical}} \times t_{\text{backup}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (480 \times 5) \div (48 \times 0.7)$
3. Calculate the top: $480 \times 5 = 2400 \text{ Wh}$
4. Calculate the bottom: $48 \times 0.7 = 33.6$
5. Divide: $C_{\text{bank}} = 2400 \div 33.6 \approx 71.4 \text{ Ah}$
6. Batteries in series for 48 V: $48 \div 12 = 4 \text{ per string}$
7. Strings in parallel for capacity: $71.4 \div 100 \approx 0.71 \rightarrow \text{round up to 1 string}$

8. Total batteries: 4 in series $\times$ 1 string = 4 batteries, giving an actual 100 Ah

At least 71.4 Ah is needed; four 12 V, 100 Ah batteries wired in series (4S1P) give 48 V, 100 Ah — already enough with a single string.

Problem 8 [Standard] A family's average daily consumption is 9 kWh. Compare two design approaches for the same home: (a) grid-lean, an 80% offset target using an annual average peak sun hours of 5.0 h/day and PR = 0.80; (b) self-reliant, sized to cover close to the full daily need using a design-month peak sun hours of 2.8 h/day and the same PR. Find the array size for each, and how many times bigger the self-reliant array is.

Solution

1. (a) $P_{\text{array}} = (\text{Offset} \times E_{\text{daily}}) \div (\text{PSH}_{\text{avg}} \times \text{PR}) = (0.80 \times 9000) \div (5.0 \times 0.80) = 7200 \div 4.0 = 1800 \text{ W}$

2. (b) $P_{\text{array}} = E_{\text{daily}} \div (\text{PSH}_{\text{design}} \times \text{PR}) = 9000 \div (2.8 \times 0.80) = 9000 \div 2.24 \approx 4017.9 \text{ W}$

3. Compare: $4017.9 \div 1800 \approx 2.23$ — about 2.2 times bigger

The grid-lean array needs 1800 W; the self-reliant array needs about 4017.9 W — roughly 2.2 times bigger, for far less reliance on the grid.

Problem 9 [Standard] Before adding solar, a family's generator supplied all 3600 Wh of their evening outage energy, running at an average loading of 1200 W. After adding a hybrid system, a battery now supplies 2400 Wh of that need before the generator starts. Find (a) the generator hours needed before, (b) the generator hours needed after, (c) the percent reduction in generator hours.

Solution

1. (a) $t_{\text{gen}}(\text{before}) = E_{\text{outage}} \div P_{\text{gen}} = 3600 \div 1200 = 3.0 \text{ h}$

2. Energy still needed after the battery: $E_{\text{gen}} = 3600 - 2400 = 1200 \text{ Wh}$

3. (b) $t_{\text{gen}}(\text{after}) = 1200 \div 1200 = 1.0 \text{ h}$

4. (c) Reduction = $(3.0 - 1.0) \div 3.0 \times 100 \approx 66.7\%$

Generator hours drop from 3.0 h to 1.0 h — a reduction of about 66.7%.

Problem 10 [Challenge] A small clinic in a Kurdistan Region town has an average daily energy consumption of 18 kWh. The clinic wants a hybrid system. (a) Size the array for a 65% offset, using an annual average peak sun hours of 5.2 h/day and PR = 0.80, and choose a number of 450 W panels. (b) The clinic's critical loads (lights, a medicine refrigerator, and some equipment) total 900 W, and the typical daily grid outage is 5 hours. Using a 48 V system and LiFePO₄ batteries (DoD = 0.8), find the required battery capacity in Ah, and the number of 12 V, 200 Ah batteries needed (series and parallel). (c) On an unusual day, maintenance work on the grid line stretches the outage to 9 hours instead of 5. Using the FULL usable energy of the battery bank installed in (b) — system voltage $\times$ actual Ah $\times$ DoD — find how long the generator must run to cover the rest of that day's 900 W outage need, running at an average loading of 1800 W. (d) Find the percent reduction in generator hours this battery gives, compared with having no battery at all for this same 9-hour outage.

Solution

1. (a) $P_{\text{array}} = (0.65 \times 18,000) \div (5.2 \times 0.80) = 11,700 \div 4.16 \approx 2812.5 \text{ W}$. Panels: $2812.5 \div 450 \approx 6.25 \rightarrow$ round up to 7 panels = 3150 W

2. (b) $E = 900 \times 5 = 4500 \text{ Wh}$. $C_{\text{bank}} = 4500 \div (48 \times 0.8) = 4500 \div 38.4 \approx 117.2 \text{ Ah}$. Series: $48 \div 12 = 4$. Parallel: $117.2 \div 200 \approx 0.59 \rightarrow$ round up to 1 string. Total: $4 \times 1 = 4$ batteries, actual 200 Ah

3. (c) Usable battery energy = $V_{\text{sys}} \times \text{actual Ah} \times \text{DoD} = 48 \times 200 \times 0.8 = 7680 \text{ Wh}$. Extended outage need:

$900 \times 9 = 8100$ Wh. Energy still needed: $8100 - 7680 = 420$ Wh. Generator time: $420 \div 1800 \approx 0.233$ h ≈ 14 minutes

4. (d) Without any battery, the generator alone would need: $8100 \div 1800 = 4.5$ h. Reduction = $(4.5 - 0.233) \div 4.5 \times 100 \approx 94.8\%$

Array: about 2812.5 W minimum, seven 450 W panels (3150 W). Battery: about 117.2 Ah minimum, four 12 V, 200 Ah batteries (4S1P, 200 Ah actual). On the extended 9-hour outage, the generator needs only about 14 minutes — a reduction of about 94.8% compared with having no battery at all.

Problem 11 [Challenge] A household's solar system produces 20 kWh on an average day. Of this, 8 kWh is used directly in the home (self-consumption), and the rest is exported. The home's total daily consumption is 24 kWh. Using an example import tariff of 120 IQD/kWh: (a) find the daily energy exported and imported. (b) find the daily bill under true net metering (export credited at the same 120 IQD/kWh rate). (c) find the daily bill under a net billing example, where export is credited at only 45 IQD/kWh. (d) compare both bills with the no-solar bill (24 kWh, all imported), and state which arrangement benefits the household more.

Solution

1. (a) Exported = production – self-consumed = $20 - 8 = 12$ kWh. Imported = total consumption – self-consumed = $24 - 8 = 16$ kWh

2. (b) True net metering: Bill = (Import – Export) $\times$ tariff = $(16 - 12) \times 120 = 4 \times 120 = 480$ IQD

3. (c) Net billing: Bill = (Import $\times$ import tariff) – (Export $\times$ export tariff) = $(16 \times 120) - (12 \times 45) = 1920 - 540 = 1380$ IQD

4. (d) No-solar bill = $24 \times 120 = 2880$ IQD. Net metering saving: $2880 - 480 = 2400$ IQD ($\approx 83.3\%$). Net billing saving: $2880 - 1380 = 1500$ IQD ($\approx 52.1\%$)

Net metering gives a much smaller bill (480 IQD) than net billing (1380 IQD) for the exact same solar system, because net billing pays less for the 12 kWh exported. Net metering saves about 83.3% of the no-solar bill; net billing saves about 52.1%. This is why confirming the local billing arrangement (Lesson 2) matters so much before promising a family a certain saving.

Problem 12 [Challenge] A rural primary school has an average daily consumption of 14 kWh, from lights, fans, computers, and a water pump. The school wants a hybrid system with a 75% offset target. (a) Using an annual average peak sun hours of 5.4 h/day and PR = 0.80, find the minimum array size and choose a number of 400 W panels. (b) The school's critical loads during a power cut — lights and computers only, no fans or pump — total 260 W, and the typical daily grid outage is 6 hours. Using a 24 V system and AGM batteries (DoD = 0.6), find the required battery Ah, and the battery count using 12 V, 100 Ah batteries (series and parallel). (c) One evening, the battery had already used some of its charge earlier in the day, so only 1200 Wh of usable battery energy is left for the evening backup. The generator supplies the rest of the $260 \text{ W} \times 6 \text{ h}$ outage need, running at an average loading of 900 W. Find the new generator run time, and the percent reduction compared with having no battery at all that evening.

Solution

1. (a) $P_{\text{array}} = (0.75 \times 14,000) \div (5.4 \times 0.80) = 10,500 \div 4.32 \approx 2430.6$ W. Panels: $2430.6 \div 400 \approx 6.08 \rightarrow$ round up to 7 panels = 2800 W

2. (b) $E = 260 \times 6 = 1560$ Wh. $C_{\text{bank}} = 1560 \div (24 \times 0.6) = 1560 \div 14.4 \approx 108.3$ Ah. Series: $24 \div 12 = 2$. Parallel: $108.3 \div 100 \approx 1.08 \rightarrow$ round up to 2 strings. Total: $2 \times 2 = 4$ batteries, actual 200 Ah

3. (c) Outage need: $260 \times 6 = 1560$ Wh, as in part (b). Energy still needed from the generator: $1560 - 1200 = 360$ Wh. Generator time: $360 \div 900 = 0.4$ h = 24 minutes

4. Without any battery: $t_{\text{gen}}(\text{no battery}) = 1560 \div 900 \approx 1.733 \text{ h}$. Reduction = $(1.733 - 0.4) \div 1.733 \times 100 \approx 76.9\%$

Array: about 2430.6 W minimum, seven 400 W panels (2800 W). Battery: about 108.3 Ah minimum, four 12 V, 100 Ah batteries (252P, 200 Ah actual). That evening, with only 1200 Wh of battery charge available, the generator needed just 0.4 hours (24 minutes) — a reduction of about 76.9% compared with no battery at all.

CHAPTER FOURTEEN

Solar Water Pumping

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the main difference between a surface pump and a submersible pump?

- A. A surface pump sits above the water and pulls it up; a submersible pump works underwater and pushes water up
- B. A surface pump only works with AC power; a submersible pump only works with DC power
- C. A surface pump is always more powerful than a submersible pump

Answer: A surface pump sits above the water and pulls it up; a submersible pump works underwater and pushes water up. A surface pump stays above the water and pulls water up by suction. A submersible pump works fully underwater, pushing water up and out. Either type can use an AC or a DC motor.

Q2. A surface pump can lift water from any depth, as long as its motor is powerful enough.

Answer: False. Suction lift is limited by air pressure to about 6–7 m in practice, no matter how strong the motor is. Beyond that depth, a submersible pump is needed instead.

Q3. Which pump-and-power combination needs a device to change the array's DC power into AC power?

- A. A DC pump
- B. An AC pump
- C. Both need this device equally

Answer: An AC pump. A DC pump can connect straight to the array through a simple pump controller. An AC pump needs its DC input changed into AC first, using an inverter or a dedicated solar pump controller.

Q4. Convert a flow rate of 3.6 m³ per hour into m³ per second.

Answer: 0.001 m³/s (± 0.00005). Divide by 3600: $3.6 \div 3600 = 0.001 \text{ m}^3/\text{s}$.

Q5. Convert a flow rate of 30 liters per minute into m³ per second.

Answer: 0.0005 m³/s (± 0.00002). Divide by 60,000: $30 \div 60,000 = 0.0005 \text{ m}^3/\text{s}$.

Q6. A pump moves water at 0.002 m³/s through a total head of 20 m. Using $\rho = 1000 \text{ kg/m}^3$ and $g = 9.81 \text{ m/s}^2$, find the hydraulic power.

Answer: 392.4 W (± 2). $P_{\text{hyd}} = \rho \times g \times Q \times H = 1000 \times 9.81 \times 0.002 \times 20 = 392.4 \text{ W}$.

Q7. A pump's static head is 15 m. Using this course's simple estimate of 10% for friction loss, what is the total dynamic head?

- A. 15.0 m
- B. 16.5 m
- C. 18.0 m

Answer: 16.5 m. Friction head loss = $10\% \times 15 = 1.5 \text{ m}$. Total dynamic head = $15 + 1.5 = 16.5 \text{ m}$.

Q8. Which of these are TRUE reasons solar pumping systems usually use a water storage tank instead of a battery? (Choose all correct answers.)

- A. A tank is usually cheaper for the same amount of 'reserve'
- B. A tank lets water be used at any time of day, even after the sun sets
- C. A tank never needs any safety precautions
- D. A full elevated tank can deliver water by gravity, without a second pump

Answer: A tank is usually cheaper for the same amount of 'reserve'; A tank lets water be used at any time of day, even after the sun sets; A full elevated tank can deliver water by gravity, without a second pump. Tanks are usually the cheaper reserve, they let stored water be used any time, and an elevated tank gives free gravity delivery. But tanks DO need safety precautions — a full tank is very heavy, and its support structure must be checked.

Q9. In this course's simple design method, a pump's array should always be sized using the coldest, lowest-sun month of the whole year, even if the pump is only used in summer.

Answer: False. A seasonal pump load should be sized using the peak sun hours of its actual pumping season, not the whole year's worst month — otherwise the array is needlessly oversized. A pump that runs all year should still follow Chapter 12's design-month rule.

Q10. A farm needs 12 m^3 of water a day, lifted through a total head of 20 m. Using the shortcut Hydraulic energy (Wh) = $2.725 \times \text{Volume} (\text{m}^3) \times \text{Head} (\text{m})$, find the daily hydraulic energy needed.

Answer: 654 Wh (± 5). $E_{\text{hyd}} = 2.725 \times 12 \times 20 = 654 \text{ Wh}$.

Q11. A pump's performance curve shows that, compared with operating at a low head, the SAME pump at a higher head will usually deliver:

- A. More flow
- B. Less flow
- C. Exactly the same flow

Answer: Less flow. Most pump curves slope downward: as head goes up, the flow the pump can deliver goes down. Always check the flow at the system's real head, not the pump's maximum 'headline' number.

Q12. Which irrigation method typically needs the smallest, steadiest flow rate, often making it the best match for a small solar pump?

- A. Flood irrigation
- B. Sprinkler irrigation
- C. Drip irrigation

Answer: Drip irrigation. Drip irrigation delivers a small, steady flow directly to each plant's roots, with high water-use efficiency (about 85–95%) — a good match for a small solar pump's limited flow rate.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] Convert a flow rate of 90 liters per minute (L/min) into m^3/s .

Solution

1. Recall: $1 \text{ m}^3/\text{s} = 60,000 \text{ L/min}$
2. Divide: $90 \div 60,000 = 0.0015 \text{ m}^3/\text{s}$

The flow rate is $0.0015 \text{ m}^3/\text{s}$.

Problem 2 [Basic] Convert a flow rate of 5000 liters per hour (L/h) into m^3/s .

Solution

1. Convert L/h to m^3/h : $5000 \div 1000 = 5 \text{ m}^3/\text{h}$
2. Convert m^3/h to m^3/s : $5 \div 3600 \approx 0.00139 \text{ m}^3/\text{s}$

The flow rate is about $0.00139 \text{ m}^3/\text{s}$ ($1.39 \times 10^{-3} \text{ m}^3/\text{s}$).

Problem 3 [Basic] A pump's static head is 12 m. Using this chapter's simple estimate of 10% for friction loss, find the total dynamic head.

Solution

1. Friction head loss: $10\% \times 12 \text{ m} = 1.2 \text{ m}$
2. Total dynamic head: $H = 12 + 1.2 = 13.2 \text{ m}$

The total dynamic head is 13.2 m.

Problem 4 [Basic] A pump moves water at $0.001 \text{ m}^3/\text{s}$ through a total dynamic head of 15 m. Find the hydraulic power. (Use $\rho = 1000 \text{ kg/m}^3$, $g = 9.81 \text{ m/s}^2$.)

Solution

1. Write the equation: $P_{\text{hyd}} = \rho \times g \times Q \times H$
2. Put in the numbers: $P_{\text{hyd}} = 1000 \times 9.81 \times 0.001 \times 15 = 147.15 \text{ W}$

The hydraulic power is about 147.15 W ($\approx 147 \text{ W}$).

Problem 5 [Standard] A pump delivers 60 liters per minute through a total dynamic head of 18 m. Find (a) the flow rate in m^3/s and (b) the hydraulic power.

Solution

1. (a) Convert flow: $60 \div 60,000 = 0.001 \text{ m}^3/\text{s}$
2. (b) Write the equation: $P_{\text{hyd}} = \rho \times g \times Q \times H$
3. Put in the numbers: $P_{\text{hyd}} = 1000 \times 9.81 \times 0.001 \times 18 = 176.58 \text{ W}$

The flow rate is $0.001 \text{ m}^3/\text{s}$, giving a hydraulic power of about 176.6 W.

Problem 6 [Standard] A borehole's resting water level is 10 m below ground. While pumping, drawdown adds another 2 m. The delivery pipe then rises 3 m further to reach the tank. Estimate friction loss as 10% of the static head. Find the total dynamic head.

Solution

1. Static head: $10 + 2 + 3 = 15 \text{ m}$ (resting depth + drawdown + rise to tank)
2. Friction head loss: $10\% \times 15 = 1.5 \text{ m}$
3. Total dynamic head: $H = 15 + 1.5 = 16.5 \text{ m}$

The total dynamic head is 16.5 m.

Problem 7 [Standard] A pump needs 250 W of hydraulic power. Its pump-and-motor efficiency is 40%. Find the electrical input power it needs.

Solution

1. Write the equation: $P_{\text{input}} = P_{\text{hyd}} \div \eta_{\text{pump}}$
2. Put in the numbers: $P_{\text{input}} = 250 \div 0.40 = 625 \text{ W}$

The pump needs 625 W of electrical input power.

Problem 8 [Standard] A village well must supply 8 m³ of water a day through a total dynamic head of 22 m. The pump-and-motor efficiency is 40%. Find (a) the daily hydraulic energy and (b) the daily electrical energy needed.

Solution

1. (a) $E_{\text{hyd}} = 2.725 \times V_{\text{daily}} \times H = 2.725 \times 8 \times 22 = 479.6 \text{ Wh}$

2. (b) $E_{\text{elec}} = E_{\text{hyd}} \div \eta_{\text{pump}} = 479.6 \div 0.40 = 1199 \text{ Wh}$

The well needs 479.6 Wh of hydraulic energy and 1199 Wh (about 1.2 kWh) of electrical energy per day.

Problem 9 [Standard] Using the village well's electrical energy need from the last problem (1199 Wh/day), with peak sun hours of 6.0 h/day and a performance ratio of 0.80, find the minimum array size.

Solution

1. Write the equation: $P_{\text{array}} = E_{\text{elec}} \div (\text{PSH} \times \text{PR})$

2. Multiply the bottom: $\text{PSH} \times \text{PR} = 6.0 \times 0.80 = 4.8$

3. Divide: $P_{\text{array}} = 1199 \div 4.8 \approx 249.8 \text{ W}$

The minimum array size is about 249.8 W (0.25 kWp).

Problem 10 [Challenge] A cooperative farm needs 25 m³ of water a day for its greenhouses, lifted through a total dynamic head of 28 m. The chosen pump-and-motor combination is 44% efficient. (a) Find the daily hydraulic energy. (b) Find the daily electrical energy needed. (c) Using the growing season's example peak sun hours of 7.0 h/day and a performance ratio of 0.78, find the minimum array size and choose a number of 450 W panels. (d) If the design had mistakenly used the region's winter peak sun hours of 3.2 h/day instead, how much bigger (in %) would the wrongly sized array be?

Solution

1. (a) $E_{\text{hyd}} = 2.725 \times 25 \times 28 = 2.725 \times 700 = 1907.5 \text{ Wh}$

2. (b) $E_{\text{elec}} = E_{\text{hyd}} \div \eta_{\text{pump}} = 1907.5 \div 0.44 \approx 4335.2 \text{ Wh}$

3. (c) $\text{PSH} \times \text{PR} = 7.0 \times 0.78 = 5.46$; $P_{\text{array}} = 4335.2 \div 5.46 \approx 794.0 \text{ W}$; panels needed: $794.0 \div 450 \approx 1.76 \rightarrow$ round up to 2 panels = 900 W

4. (d) Winter sizing: $\text{PSH} \times \text{PR} = 3.2 \times 0.78 = 2.496$; $P_{\text{array}}(\text{winter}) = 4335.2 \div 2.496 \approx 1736.9 \text{ W}$

5. Compare: $(1736.9 - 794.0) \div 794.0 \times 100\% \approx 118.75\%$, so the wrongly sized array would be about 119% bigger — more than double

The greenhouse system needs about 1907.5 Wh of hydraulic energy and 4335.2 Wh of electrical energy per day. Sized for the growing season (7.0 h/day), the array needs about 794 W — two 450 W panels (900 W total). Sized incorrectly for winter (3.2 h/day), it would need about 1737 W — about 119% bigger, more than double, and a waste of money for a pump that never runs in winter.

Problem 11 [Challenge] A farm's daily irrigation need is 14 m³ of water. During the growing season, cloudy runs of up to 3 days sometimes occur. Using this chapter's tank-sizing method, (a) find the minimum tank capacity needed to cover 3 days of reserve. (b) If tanks are locally available only in a standard 10 m³ size, how many tanks should the farm buy, and what is the real total capacity?

Solution

1. (a) $V_{\text{tank}} = V_{\text{daily}} \times N_{\text{store}} = 14 \times 3 = 42 \text{ m}^3$
2. (b) Number of tanks: $42 \div 10 = 4.2 \rightarrow$ round up to 5 whole tanks
3. Real total capacity: $5 \times 10 = 50 \text{ m}^3$

The farm needs at least 42 m³ of storage. Buying five 10 m³ tanks gives a real total of 50 m³ — a little more than the minimum, which is normal when rounding up to real, whole equipment.

Problem 12 [Challenge] A remote livestock watering station needs 6 m³ of water a day. The borehole's total dynamic head is 40 m. The submersible pump chosen has a pump-and-motor efficiency of 38%, and its performance curve shows it delivers 25 L/min when working against a 40 m head. (a) Find the daily hydraulic and electrical energy needed. (b) Using a year-round peak sun hours value of 5.5 h/day (this station is needed every day of the year, so Chapter 12's design-month rule applies) and a performance ratio of 0.75, find the minimum array size. (c) Running at its rated 25 L/min, how many hours would the pump need to run to pump the full daily need, and is this realistic within the available sun hours?

Solution

1. (a) $E_{\text{hyd}} = 2.725 \times 6 \times 40 = 2.725 \times 240 = 654 \text{ Wh}$; $E_{\text{elec}} = 654 \div 0.38 \approx 1721.1 \text{ Wh}$
2. (b) $\text{PSH} \times \text{PR} = 5.5 \times 0.75 = 4.125$; $P_{\text{array}} = 1721.1 \div 4.125 \approx 417.2 \text{ W}$
3. (c) Convert daily volume to liters: $6 \text{ m}^3 = 6000 \text{ L}$; running time: $t = V \div Q = 6000 \text{ L} \div 25 \text{ L/min} = 240 \text{ minutes} = 4.0 \text{ hours}$
4. Compare: 4.0 hours of pumping fits comfortably inside the 5.5 available peak sun hours, leaving about 1.5 hours of margin for a hazier day

The station needs about 654 Wh of hydraulic energy and 1721.1 Wh of electrical energy per day, needing an array of about 417 W. Running at its rated flow, the pump needs only about 4.0 hours to deliver the full daily need — comfortably inside the 5.5-hour sun day, with a useful safety margin for cloudier days.

CHAPTER FIFTEEN

Money and the Environment

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the 'capital cost' of a solar system?

- A. The one-time cost to buy and install it
- B. The monthly cost of running it
- C. The cost of electricity from the grid

Answer: **The one-time cost to buy and install it.** *Capital cost is the one-time, upfront money paid to buy and install the whole system. Ongoing costs like fuel and maintenance are called operating costs.*

Q2. Which of these are part of the 'balance of system' (BOS)? (Choose all correct answers.)

- A. Charge controller
- B. Solar panels
- C. Inverter
- D. Cables and mounting structure

Answer: **Charge controller; Inverter; Cables and mounting structure.** *Balance of system means every part of a solar system EXCEPT the panels and batteries — so the charge controller, inverter, cables, and mounting structure all count, but the panels do not.*

Q3. In this chapter's example system, the solar panels are the single most expensive part.

Answer: **False.** *In the example cost breakdown, the batteries were the biggest share (35%), more than the panels (25%). This is common for systems with battery storage.*

Q4. A system costs 4,000,000 IQD. Its inverter costs 600,000 IQD. What percentage of the total cost is the inverter?

Answer: **15 % (± 0.5).** *Percentage share = (part cost ÷ total cost) × 100 = (600,000 ÷ 4,000,000) × 100 = 15%.*

Q5. What does the levelized cost of energy (LCOE) tell you?

- A. The average cost of one kWh of energy over a system's whole life
- B. The total cost to buy a system
- C. The price of electricity from the grid only

Answer: **The average cost of one kWh of energy over a system's whole life.** *LCOE is a simple way to compare energy sources fairly: it spreads the total cost over the total energy produced, giving one cost-per-kWh number.*

Q6. A solar system costs 6,000,000 IQD (example numbers). Over a 20-year lifetime it produces 4,000 kWh per year. What is its simple LCOE, in IQD per kWh?

Answer: **75 IQD/kWh (± 2).** *$LCOE = C ÷ (E × n) = 6,000,000 ÷ (4,000 × 20) = 6,000,000 ÷ 80,000 = 75$ IQD/kWh.*

Q7. In this course's example numbers, generator electricity almost always costs LESS per kWh than grid electricity.

Answer: **False.** *The opposite is true. In the example numbers, the generator costs about 380 IQD/kWh — nearly four times the example grid tariff of 100 IQD/kWh — because a subscription's fuel and running costs are spread over less energy than the grid.*

Q8. A solar system costs 5,000,000 IQD (example numbers) and saves its owner 1,250,000 IQD per year. What is the simple payback period, in years?

Answer: 4 years (± 0.1). *Payback period = System cost $\div$ Annual savings = 5,000,000 $\div$ 1,250,000 = 4 years.*

Q9. Which of these should a careful lifetime-savings estimate include? (Choose all correct answers.)

- A. The system's capital cost
- B. Battery or inverter replacement during its life
- C. Ongoing maintenance costs
- D. The color of the panels

Answer: The system's capital cost; Battery or inverter replacement during its life; Ongoing maintenance costs. *A full lifetime-savings estimate should subtract the capital cost, any battery or inverter replacement, and maintenance. Panel color has no effect on cost or performance.*

Q10. A solar system produces 3000 kWh in one year. Using the example emission factor of 0.7 kg CO₂ per kWh, how much CO₂ does it avoid in one year, in kg?

Answer: 2100 kg (± 20). *CO₂ avoided = Energy $\times$ emission factor = 3000 kWh $\times$ 0.7 kg CO₂/kWh = 2100 kg CO₂.*

Q11. Why is 0.7 kg CO₂ per kWh called an 'illustrative' emission factor in this chapter?

- A. It is a reasonable example value used for teaching, not a precise measured local number
- B. It is the exact factor for every diesel generator in the world
- C. It has nothing to do with generators

Answer: It is a reasonable example value used for teaching, not a precise measured local number. *The course uses 0.7 kg CO₂/kWh as a clear, consistent teaching example for diesel generation. Real emission factors vary by fuel, technology, and efficiency; sourced local data comes later, in Chapter 21.*

Q12. A shorter financing (installment) period than the payback period can mean the monthly payment is bigger than the monthly savings, at least until the loan is paid off.

Answer: True. *Yes. In Lesson 3's example, a 24-month loan ($\approx 333,300$ IQD/month) cost more per month than the average savings ($\approx 167,800$ IQD/month) during the loan. After the loan is paid off, the full monthly saving belongs to the owner.*

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A system costs 6,000,000 IQD in total (example numbers). The battery bank costs 1,800,000 IQD. What percentage of the total cost is the battery bank?

Solution

1. Write the equation: $S = (c \div C) \times 100$
2. Put in the numbers: $S = (1,800,000 \div 6,000,000) \times 100$
3. Calculate: $S = 0.30 \times 100 = 30\%$

The battery bank is 30% of the total system cost.

Problem 2 [Basic] A small generator subscription costs 30,000 IQD per month (example numbers). In a realistic month it delivers about 90 kWh of energy. What is the real cost per kWh?

Solution

1. Write the idea: cost per kWh = total cost ÷ total energy
2. Put in the numbers: 30,000 IQD ÷ 90 kWh
3. Calculate: ≈ 333 IQD/kWh

The generator's real cost is about 333 IQD per kWh.

Problem 3 [Basic] A small solar system costs 3,000,000 IQD (example numbers). It saves the owner 750,000 IQD per year. What is the simple payback period?

Solution

1. Write the equation: $T = C \div S$
2. Put in the numbers: $T = 3,000,000 \div 750,000$
3. Calculate: $T = 4.0$ years

The system pays for itself in 4.0 years.

Problem 4 [Basic] A solar system produces 2000 kWh in one year. Using the example emission factor of 0.7 kg CO₂ per kWh, how much CO₂ does it avoid in one year, in kg and in tonnes?

Solution

1. Write the equation: $M = E \times f$
2. Put in the numbers: $M = 2000 \text{ kWh} \times 0.7 \text{ kg CO}_2/\text{kWh}$
3. Calculate: $M = 1400 \text{ kg CO}_2$
4. Convert to tonnes: $1400 \div 1000 = 1.4$ tonnes

The system avoids 1400 kg, which is 1.4 tonnes, of CO₂ in one year.

Problem 5 [Standard] A small off-grid system has these example costs: panels 1,500,000 IQD, batteries 1,500,000 IQD, controller 250,000 IQD, inverter 900,000 IQD, cabling and mounting 350,000 IQD, installation 500,000 IQD. Find (a) the total system cost, and (b) the percentage share of the batteries and the inverter.

Solution

1. Add every part: $1,500,000 + 1,500,000 + 250,000 + 900,000 + 350,000 + 500,000 = 5,000,000$ IQD
2. Batteries share: $(1,500,000 \div 5,000,000) \times 100 = 30\%$
3. Inverter share: $(900,000 \div 5,000,000) \times 100 = 18\%$

The total cost is 5,000,000 IQD. The batteries are 30% of the cost and the inverter is 18%.

Problem 6 [Standard] An off-grid system costs 5,000,000 IQD (example numbers, see Problem 5) and is expected to produce 2500 kWh per year. Assuming a 20-year working life, what is its simple cost per kWh (LCOE)?

Solution

1. Write the equation: $LCOE = C \div (E \times n)$
2. Put in the numbers: $LCOE = 5,000,000 \div (2500 \times 20)$
3. Calculate the lifetime energy: $2500 \times 20 = 50,000$ kWh
4. Calculate: $LCOE = 5,000,000 \div 50,000 = 100$ IQD/kWh

The system's simple LCOE is 100 IQD per kWh.

Problem 7 [Standard] A 2 kWp array gets 5 peak sun hours per day in an example location. The system's performance ratio is 0.75. Find (a) the daily energy production, and (b) the annual energy production (use 365 days).

Solution

1. Daily production: $E = \text{array size} \times \text{sun hours} \times \text{performance ratio}$
2. Put in the numbers: $E = 2 \text{ kWp} \times 5 \text{ h} \times 0.75 = 7.5 \text{ kWh/day}$
3. Annual production: $7.5 \text{ kWh/day} \times 365 \text{ days} = 2737.5 \approx 2738 \text{ kWh/year}$

The array produces about 7.5 kWh per day, or about 2738 kWh per year.

Problem 8 [Standard] A family's solar system cost 4,500,000 IQD (example numbers). It produces 3000 kWh per year, replacing generator electricity that costs about 300 IQD/kWh (example price). Find (a) the annual savings, and (b) the simple payback period.

Solution

1. Annual savings: $S = E \times \text{price} = 3000 \text{ kWh} \times 300 \text{ IQD/kWh} = 900,000 \text{ IQD/year}$
2. Write the payback equation: $T = C \div S$
3. Put in the numbers: $T = 4,500,000 \div 900,000 = 5.0 \text{ years}$

The system saves 900,000 IQD per year and pays for itself in 5.0 years.

Problem 9 [Standard] In one example comparison, solar costs about 80 IQD/kWh (LCOE) and the grid costs 120 IQD/kWh (example tariff). (a) How many IQD cheaper is solar, per kWh? (b) What percentage cheaper is solar than the grid?

Solution

1. Difference: $120 - 80 = 40 \text{ IQD/kWh}$
2. Percentage cheaper: $(40 \div 120) \times 100 \approx 33.3\%$

Solar is 40 IQD/kWh cheaper than the grid in this example — about 33.3% cheaper.

Problem 10 [Standard] A solar system avoids 2800 kg of CO₂ per year. Using an illustrative absorption rate of 20 kg CO₂ per tree per year, how many trees would be needed to absorb the same amount of CO₂?

Solution

1. Write the idea: $\text{number of trees} = \text{CO}_2 \text{ avoided} \div \text{CO}_2 \text{ absorbed per tree}$
2. Put in the numbers: $2800 \text{ kg} \div 20 \text{ kg per tree}$
3. Calculate: 140 trees

It would take about 140 trees to absorb the same CO₂, in this illustrative comparison.

Problem 11 [Challenge] A hybrid solar system for a small clinic costs 12,000,000 IQD in total (example numbers). Its array produces 20 kWh per day on average. The clinic previously relied on a generator costing about 350 IQD/kWh (example, realistic use). Assume a 20-year system life. Find: (a) the annual energy production, (b) the

annual savings, (c) the simple payback period, (d) the net lifetime savings over 20 years (ignore maintenance and replacement costs).

Solution

1. (a) Annual production: $20 \text{ kWh/day} \times 365 \text{ days} = 7300 \text{ kWh/year}$
2. (b) Annual savings: $7300 \text{ kWh/year} \times 350 \text{ IQD/kWh} = 2,555,000 \text{ IQD/year}$
3. (c) Payback: $T = C \div S = 12,000,000 \div 2,555,000 \approx 4.7 \text{ years}$
4. (d) Lifetime value of energy: $2,555,000 \times 20 = 51,100,000 \text{ IQD}$
5. (d) Net lifetime savings: $51,100,000 - 12,000,000 = 39,100,000 \text{ IQD}$

The clinic's system produces about 7300 kWh/year, saves about 2,555,000 IQD/year, pays back in about 4.7 years, and nets about 39,100,000 IQD over 20 years (before maintenance or replacement costs).

Problem 12 [Challenge] Two solar systems are compared using the illustrative emission factor of 0.7 kg CO₂/kWh and a 20-year lifetime for both. System A produces 4000 kWh/year. System B produces 9000 kWh/year. Find (a) the lifetime CO₂ avoided by each system, in tonnes, and (b) how many times more CO₂ System B avoids compared to System A.

Solution

1. System A lifetime CO₂: $4000 \text{ kWh/year} \times 0.7 \text{ kg/kWh} \times 20 \text{ years} = 56,000 \text{ kg} = 56 \text{ tonnes}$
2. System B lifetime CO₂: $9000 \text{ kWh/year} \times 0.7 \text{ kg/kWh} \times 20 \text{ years} = 126,000 \text{ kg} = 126 \text{ tonnes}$
3. Ratio: $126 \div 56 = 2.25$

System A avoids 56 tonnes and System B avoids 126 tonnes over 20 years — System B avoids 2.25 times as much, matching the ratio of their energy production ($9000 \div 4000 = 2.25$).

Problem 13 [Challenge] A shop owner buys a 6,000,000 IQD solar system (example numbers) using a 12-month, interest-free installment plan (example terms). The system saves the shop about 1,800,000 IQD per year in avoided generator costs. Find (a) the monthly installment payment, (b) the average monthly savings, (c) the net monthly cash flow during the 12-month installment period (savings minus payment) — is it positive or negative? (d) After the 12 months, how much does the shop save per month with nothing owed?

Solution

1. (a) Monthly payment: $6,000,000 \div 12 = 500,000 \text{ IQD/month}$
2. (b) Monthly savings: $1,800,000 \div 12 = 150,000 \text{ IQD/month}$
3. (c) Net cash flow: $150,000 - 500,000 = -350,000 \text{ IQD/month}$ — negative, the shop pays more than it saves during the loan
4. (d) After month 12, the loan is finished, so the shop keeps the full 150,000 IQD/month saving

During the 12-month loan the shop's net cash flow is -350,000 IQD per month. After the loan is paid off, the shop saves the full 150,000 IQD per month with nothing owed.

CHAPTER SIXTEEN

Site Assessment and System Planning

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the main purpose of a site survey?

- A. To check, measure, and record everything needed before designing or installing a solar system
- B. To sell equipment to the customer as quickly as possible
- C. To test a finished system's performance after installation

Answer: To check, measure, and record everything needed before designing or installing a solar system.

A site survey happens BEFORE a design is finalized and before equipment is bought. It collects the real facts — roof condition, usable area, shading, and more — that every later calculation depends on. Testing a finished system is covered in Chapter 18.

Q2. A solar site survey should always include a check of the roof's or structure's load-bearing capacity.

Answer: True. Panels, racks, wind, and workers all add real weight and force to a roof. Checking load-bearing capacity — and involving a structural engineer when in doubt — is a core part of every site survey, not an optional extra.

Q3. Which of these should be recorded during a site survey? (Choose all correct answers.)

- A. Roof or structure condition and material
- B. The usable area for the array
- C. Nearby obstructions and shading
- D. The customer's favorite color

Answer: Roof or structure condition and material; The usable area for the array; Nearby obstructions and shading. A site survey records facts that affect the design and installation: condition, usable area, and shading are all essential. A customer's favorite color has no effect on a solar system's engineering.

Q4. A roof has a total area of 150 m². Obstructions take up 12 m², and the required setback takes up 18 m². What is the usable roof area, in m²?

Answer: 120 m² (± 1). Usable area = Total roof area – Area lost to obstructions – Area lost to setbacks = 150 – 12 – 18 = 120 m².

Q5. Which tool is used to measure an angle above the horizontal, such as a roof's pitch or an obstruction's height angle?

- A. Clinometer
- B. Multimeter
- C. Circuit breaker

Answer: Clinometer. A clinometer measures angles above the horizontal. A multimeter (Chapter 2) measures electrical values, and a circuit breaker (Chapter 9) is a protection device, not a measuring tool.

Q6. A simple compass always points to true south, with no correction needed.

Answer: False. A simple compass points to magnetic south, which is usually a few degrees away from true south. This difference is the magnetic declination (Chapter 5), and it must be corrected for accurate orientation readings.

Q7. An obstruction is 5 m higher than the array and 10 m away, measured horizontally. What is the obstruction angle, in degrees?

Answer: 26.57 degrees (± 1). $\theta = \arctan(h \div d) = \arctan(5 \div 10) = \arctan(0.5) \approx 26.6^\circ$.

Q8. Why is it important to check shading across ALL seasons, not only in summer?

- A. Because the Sun is lower in the sky in winter, so shadows are longer
- B. Because solar panels only produce electricity in summer
- C. Because obstructions physically move to new positions in winter

Answer: Because the Sun is lower in the sky in winter, so shadows are longer. *The Sun's altitude is lowest around the December solstice (Chapter 3), which makes shadows longest. An obstruction that misses the array in summer can shade it badly in winter — exactly the case in this lesson's worked example and case study.*

Q9. Which of these normally appear on a single-line diagram (SLD)? (Choose all correct answers.)

- A. The solar array
- B. The charge controller and inverter
- C. Every single screw and cable clip
- D. Breakers, disconnects, and earthing

Answer: The solar array; The charge controller and inverter; Breakers, disconnects, and earthing. *An SLD shows the main components and how they connect — array, controller, inverter, and protection/earthing — using one line per circuit. It does not show every small physical part like screws and clips; that level of detail belongs to the physical installation, not the diagram.*

Q10. What is a bill of materials (BOM)?

- A. A complete list of every part needed for a project, with the quantity of each
- B. A drawing of the roof seen from above
- C. A test of the battery bank's voltage

Answer: A complete list of every part needed for a project, with the quantity of each. *A bill of materials lists every part and its quantity, usually built directly from the single-line diagram. A site plan is the drawing from above, and testing voltage is covered in Chapter 18.*

Q11. A good quotation should clearly state the scope of work — what is, and is not, included.

Answer: True. *A written scope of work protects both the customer and the installer from misunderstandings and disputes, as this chapter's case study showed.*

Q12. A job's total cost (materials + labor + contingency) is 5,000,000 IQD. The supplier adds a 20% margin. What is the quotation price, in IQD?

Answer: 6000000 IQD (± 50000). $P = C \times (1 + m) = 5,000,000 \times (1 + 0.20) = 5,000,000 \times 1.20 = 6,000,000$ IQD.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A site survey finds visible cracks and water stains on a flat concrete roof where a family wants to install solar panels. What should the surveyor recommend before any design work continues?

Solution

1. Cracks and water stains are warning signs that the roof structure may be weaker than it looks.
2. A solar array, its mounting rack, and wind load all add real extra weight and force to the roof (Chapter 5).
3. The safe next step is to pause the design and bring in a qualified structural engineer to check the roof's load-bearing capacity, exactly as this chapter's case study describes.

The surveyor should recommend a structural engineer's inspection before the project continues — checking load-bearing capacity always comes before finalizing a design.

Problem 2 [Basic] A roof is 10 m by 8 m. Obstructions on the roof take up 6 m² of space, and the required setback takes up 10 m². Find the usable roof area.

Solution

1. Find the total roof area: $10\text{ m} \times 8\text{ m} = 80\text{ m}^2$
2. Subtract the area lost to obstructions: $80 - 6 = 74\text{ m}^2$
3. Subtract the area lost to the setback: $74 - 10 = 64\text{ m}^2$

The usable roof area is 64 m².

Problem 3 [Basic] List the four main groups of information a complete site survey should record.

Solution

1. Recall this chapter's checklist: building and roof/ground condition; usable space and measurements; orientation, tilt, and shading; the existing electrical system, access route, and photos.
2. Group these into four main areas: structure/condition, space/measurements, orientation/shading, and electrical/access/photos.

A complete survey records: structure condition and load-bearing capacity; usable area and measurements; orientation and shading; and the electrical system, access, and photos.

Problem 4 [Basic] Why should a surveyor take photos during a site visit, even after writing detailed notes?

Solution

1. Written notes can miss small details, or be misread later.
2. A photo lets someone who was not on site — an engineer, a supplier, a second opinion — see the actual conditions.
3. Photos also become part of the project's record, useful for the quotation, the installation plan, and any future dispute or warranty question.

Photos back up written notes with real evidence, let people who were not on site review conditions, and become a lasting project record.

Problem 5 [Basic] A wall is 6 m long. You draw it as a 6 cm line on paper. What is the scale of your drawing?

Solution

1. Convert both lengths to the same unit: $6\text{ m} = 600\text{ cm}$
2. Write the equation: $\text{Scale} = L_{\text{drawing}} \div L_{\text{real}}$
3. Put in the numbers: $\text{Scale} = 6\text{ cm} \div 600\text{ cm} = 1/100$

The scale is 1:100 — every 1 cm on the paper equals 1 m (100 cm) in real life.

Problem 6 [Standard] A chimney is 2.5 m higher than the array and 5 m away, measured horizontally. Find the obstruction angle. Will it block the sun at solar noon on the December solstice in Erbil (noon altitude about 30°, from Chapter 3)?

Solution

1. Write the equation: $\theta = \arctan(h \div d)$
2. Put in the numbers: $\theta = \arctan(2.5 \div 5) = \arctan(0.5)$
3. Calculate: $\theta \approx 26.6^\circ$
4. Compare: 26.6° is smaller than Erbil's December solstice noon altitude of about 30°

The obstruction angle is about 26.6°, which is less than the winter noon Sun altitude of about 30°, so the chimney does not block the array exactly at solar noon in winter. It could still cause shading earlier or later in the day, when the Sun is lower still.

Problem 7 [Standard] A usable roof area is 70 m². Using Panel B from Chapter 5 (about 1.94 m² each) and a 20% spacing allowance, how many panels fit, and what is the resulting array size?

Solution

1. Write the equation: $N = A_{\text{usable}} \div (A_{\text{panel}} \times f)$
 2. Put in the numbers: $N = 70 \div (1.94 \times 1.2)$
 3. Calculate the bottom: $1.94 \times 1.2 \approx 2.33 \text{ m}^2$
 4. Divide: $N = 70 \div 2.33 \approx 30.0$
 5. Round down: $N = 30$ panels
 6. Array size: $30 \times 330 \text{ W} = 9900 \text{ W} \approx 9.9 \text{ kW}$
- 30 panels fit, giving an array of about 9.9 kW.**

Problem 8 [Standard] A shading survey finds two obstructions with the same obstruction angle: one due north of the array, and one due west. Which one is more likely to actually reduce the array's energy production, and why?

Solution

1. Recall the Sun's path (Chapter 3): in the Northern Hemisphere, the Sun rises in the east, crosses through the southern sky, and sets in the west — it is almost never in the northern sky.
2. An obstruction to the west can block the Sun during the afternoon, a normally productive part of the day.
3. An obstruction to the north, even with the same obstruction angle, has almost nothing to block, because the Sun is essentially never there.

The western obstruction matters far more. Obstruction angle alone is not enough — direction matters too, because the Sun only occupies part of the sky.

Problem 9 [Standard] Materials for a job cost 4,000,000 IQD and labor costs 800,000 IQD. The company adds a 5% contingency, then a 15% margin. Find the final quotation price.

Solution

1. Add materials and labor: $4,000,000 + 800,000 = 4,800,000 \text{ IQD}$

2. Add 5% contingency: $4,800,000 \times 0.05 = 240,000$ IQD

3. Total cost: $C = 4,800,000 + 240,000 = 5,040,000$ IQD

4. Apply the margin: $P = C \times (1 + m) = 5,040,000 \times 1.15$

5. Calculate: $P \approx 5,796,000$ IQD

The quotation price is about 5,796,000 IQD (example numbers for practice).

Problem 10 [Standard] During a site survey, the surveyor finds the existing distribution board is old, has no visible earthing wire, and some breakers are unlabeled. Should this stop the solar project completely? What should the survey report recommend?

Solution

1. Missing earthing and unlabeled breakers are real safety hazards, independent of the solar system (Chapter 9).

2. The solar project can still go ahead, but the survey report must clearly record these existing problems, not just the solar-specific facts.

3. The recommendation should be to have a qualified electrician correct the earthing and labeling — either before the solar work begins, or as part of the same project — so the finished system is safe as a whole, not just its new parts.

The project does not need to stop, but the survey report must flag the missing earthing and unlabeled breakers, with a clear recommendation to fix them, since Chapter 9's safety requirements apply to the whole building, not only the new solar equipment.

Problem 11 [Standard] The array on a roof is 15 m of cable route from the equipment room where the batteries and inverter will go. The installer plans to add 3 m of extra cable at each end for routing and connections. What total cable length should appear on the bill of materials for this one run?

Solution

1. Start with the measured route distance: 15 m

2. Add the extra cable at the array end: $15 + 3 = 18$ m

3. Add the extra cable at the equipment-room end: $18 + 3 = 21$ m

The bill of materials should list 21 m of cable for this run.

Problem 12 [Challenge] A survey of a flat roof finds: total area 200 m^2 , a stairwell exit taking 8 m^2 , a water tank taking 6 m^2 , and a required setback strip taking 30 m^2 . (a) Find the usable area. (b) Using Panel A from Chapter 5 (450 W, about 2.17 m^2 each) with a 25% spacing allowance, how many panels fit? (c) What array size, in kW, does this give?

Solution

1. (a) Usable area: $200 - 8 - 6 - 30 = 156 \text{ m}^2$

2. (b) Panel footprint with spacing: $2.17 \times 1.25 \approx 2.71 \text{ m}^2$

3. (b) Number of panels: $156 \div 2.71 \approx 57.5 \rightarrow$ round down to 57 panels

4. (c) Array size: $57 \times 450 \text{ W} = 25,650 \text{ W} \approx 25.65 \text{ kW}$

The usable area is 156 m^2 , 57 panels fit, giving an array of about 25.65 kW.

Problem 13 [Challenge] A site's only significant obstruction is a tree with its top 7 m higher than the array, 10 m to the south. (a) Find the obstruction angle. (b) Using Erbil's example noon Sun altitudes (equinox 54°, June solstice 77°, December solstice 30°, from Chapter 3), in which of these three periods would the tree most likely shade the array at solar noon? (c) What does this mean for how the array's winter energy production should be planned, given that winter is already the design month in Chapter 12?

Solution

1. (a) $\theta = \arctan(h \div d) = \arctan(7 \div 10) = \arctan(0.7) \approx 35.0^\circ$
2. (b) Compare 35.0° with each noon altitude: equinox 54° (35 < 54, no block), June solstice 77° (35 < 77, no block), December solstice 30° (35 > 30, BLOCKED)
3. (b) The tree only blocks the array at solar noon around the December solstice.
4. (c) December is already the design month in Chapter 12's off-grid method, chosen because it normally has the fewest peak sun hours of the year.
5. (c) This extra shading loss makes that already-weak month even weaker, so it should be added as an extra derating factor (Chapter 12) when sizing the array for winter — or the tree should be trimmed or the array repositioned before finalizing the design.

The obstruction angle is about 35°, which blocks the array only around the December solstice — exactly the month an off-grid array is already sized around. This shading should be included as an extra loss in the design-month calculation, or removed by trimming the tree or moving the array.

Problem 14 [Challenge] Two quotations arrive for the same 5 kW system. Quotation A: 9,000,000 IQD, with a full bill of materials, a clear scope of work, a 5-year workmanship warranty, and photos of completed projects. Quotation B: 7,200,000 IQD, a one-page price with no bill of materials, no scope of work, and no warranty mentioned. (a) Find the price difference in IQD, and as a percentage of Quotation B's price. (b) List at least three questions the buyer should ask Quotation B's supplier before deciding. (c) Using this chapter's ideas, explain why the cheaper quotation might not be the better value.

Solution

1. (a) Price difference: $9,000,000 - 7,200,000 = 1,800,000$ IQD
2. (a) As a percentage of Quotation B: $(1,800,000 \div 7,200,000) \times 100 = 25\%$
3. (b) Useful questions include: What brands and models are included? Is installation labor included? What warranty applies, and for how long? What is not included? What is the payment schedule?
4. (c) A quotation with no bill of materials and no scope of work cannot be trusted to include everything needed — exactly the trap in Chapter 15's 'Three Quotations for One Roof' case study, where the cheapest quotation became the most expensive once the missing parts were added.
5. (c) Quotation A's higher price already includes a full bill of materials, a clear scope of work, and a warranty — real value that Quotation B's price does not guarantee.

Quotation A costs 1,800,000 IQD more — 25% more than Quotation B's price. But Quotation B's missing bill of materials, scope of work, and warranty mean its real final cost, and its risk, could easily end up higher. As this chapter and Chapter 15 both show, the lowest number on a quotation is not always the best value.

CHAPTER SEVENTEEN

Installation Step by Step

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. Which mounting method is most common on flat concrete roofs in Iraq and the Kurdistan Region, mainly because it avoids the risk of roof leaks?

- A. A ballasted (non-penetrating) rack
- B. A bolted (penetrating) rack
- C. No frame at all — panels lie flat
- D. Ground mount only

Answer: A ballasted (non-penetrating) rack. *A ballasted rack uses heavy weight instead of holes, so it avoids the leak risk of a roof penetration — this is why it is the usual choice on flat concrete roofs here. A bolted rack is still used sometimes, for example on very lightweight roofs or in very high wind.*

Q2. A ballasted rack needs no engineering check, because it is not bolted to the roof.

Answer: False. *A ballasted rack still adds real weight to the roof and must resist local wind load. The roof's carrying capacity and the ballast amount both need checking — for anything beyond a small system, ask a qualified person.*

Q3. Panel A is 2.094 m long (mounted up-slope) and tilted at 36° in Erbil. Using the rule-of-thumb spacing factor $k = 2$, what is the minimum row-to-row gap, in meters?

Answer: 2.46 m (± 0.15). *Rise = $L \times \sin(\beta) = 2.094 \times \sin(36^\circ) \approx 1.23$ m. Minimum gap = $k \times \text{rise} = 2 \times 1.23 \approx 2.46$ m (often rounded up to about 2.5 m in practice).*

Q4. What is the purpose of a drip loop in a cable?

- A. To let water drip off the cable before it reaches a connector or enclosure
- B. To make the cable electrically stronger
- C. To increase the cable's current rating
- D. To reduce voltage drop over long distances

Answer: To let water drip off the cable before it reaches a connector or enclosure. *A drip loop is a downward loop just before a cable enters a connector or enclosure. Water running down the cable drips off at the bottom of the loop instead of running inside.*

Q5. Which of these are correct ways to protect an outdoor DC cable? (Choose all correct answers.)

- A. Use PV-rated cable made to resist UV and weather
- B. Route it through conduit or a cable tray where it could be damaged
- C. Leave plenty of slack with no drip loop, letting it hang low straight into the equipment box
- D. Label the cable so anyone doing maintenance later knows what it is

Answer: Use PV-rated cable made to resist UV and weather; Route it through conduit or a cable tray where it could be damaged; Label the cable so anyone doing maintenance later knows what it is. *Using PV-rated cable, protecting it with conduit or tray, and labeling it are all good practice. Slack with NO drip loop is a mistake — water can run straight down the cable into the box. Slack is good, but it must be shaped into a drip loop.*

Q6. It is safe to unplug a loaded MC4 connector by hand in the middle of a sunny day, as long as you are wearing gloves.

Answer: False. A loaded DC connector can arc when pulled apart, and gloves do not stop that arc. Use a rated disconnect switch, cover the panels, or work when there is no sunlight on the string.

Q7. Why do flooded lead-acid batteries need a well-ventilated space?

- A. They release hydrogen gas while charging, which can explode if it collects and meets a spark
- B. They need fresh air to produce electricity
- C. Ventilation makes them charge faster
- D. It is only about keeping dust off the case

Answer: They release hydrogen gas while charging, which can explode if it collects and meets a spark. Flooded lead-acid batteries release hydrogen gas while charging. It is invisible and explosive if it collects in a closed space and meets a spark or flame — ventilation carries it safely away.

Q8. A rough rule of thumb says a lead-acid battery loses about half its expected life for every 10°C it runs above 25°C. A battery is rated for 6 years at 25°C. About how many years might it last in an unventilated room that stays near 35°C?

Answer: 3 years (± 0.5). 35°C is 10°C above 25°C — one halving. $6 \div 2 = 3$ years. This is only a rough guide, but it shows clearly why heat and ventilation matter so much for battery life.

Q9. What is the main danger of working on a solar array's DC wiring without first testing whether it is truly de-energized?

- A. Unlike a switched-off appliance, a lit panel always makes voltage — you cannot assume a disconnected-looking string is safe without testing
- B. DC electricity is never dangerous, at any voltage
- C. Nothing — solar panels always stop working once touched
- D. The only risk is a small tingle, never a serious shock

Answer: Unlike a switched-off appliance, a lit panel always makes voltage — you cannot assume a disconnected-looking string is safe without testing. A solar panel makes voltage the moment light reaches it. A switch or breaker that looks open does not guarantee a circuit is dead — always test and confirm with a meter before touching.

Q10. Which of these should be confirmed on a pre-power-up commissioning checklist? (Choose all correct answers.)

- A. All bolts and clamps are tight to the correct torque
- B. Correct polarity at every connection
- C. Earthing and bonding connections are made and tight
- D. It is fine to leave one small tool on the roof if it is out of the way

Answer: All bolts and clamps are tight to the correct torque; Correct polarity at every connection; Earthing and bonding connections are made and tight. Mechanical, electrical, and earthing checks all belong on the checklist. Tools and loose materials should NEVER be left behind — they are a hazard and a sign the walk-through was not finished properly.

Q11. The 4-to-1 ladder rule means that for every 4 units of height to the point the ladder rests against, the base should be moved out 1 unit.

Answer: True. This angle gives a stable, safe climbing angle. For a roof 4 m up, the base of the ladder should be set out about 1 m from the wall.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A design calls for 45 kg of ballast at one panel position. Each concrete paver weighs 9 kg. How many pavers are needed for that position?

Solution

1. Write the idea: number of pavers = total ballast needed ÷ weight of one paver
2. Put in the numbers: $45 \text{ kg} \div 9 \text{ kg} = 5$

5 pavers are needed for this panel position.

Problem 2 [Basic] List four items of personal protective equipment (PPE) a technician should wear while mounting panels on a roof in summer, and say what each one protects against.

Solution

1. Recall Lesson 4's PPE table and match each item to its main risk.
2. Choose four different items so the list covers several different risks, not the same risk twice.

A good answer names four items such as gloves, safety glasses, non-slip boots, and sun protection, each matched with the hazard it reduces.

Problem 3 [Basic] A worker wants to unplug a loaded MC4 connector by hand in full sunlight, to save the time of finding the nearest disconnect switch. Is this safe? Explain in one or two sentences.

Solution

1. Recall Chapter 9 and Lesson 4: a connector carrying current can arc when separated under load.
2. Recall that DC arcs are more dangerous than many AC arcs because they do not self-extinguish as easily.

No, it is not safe. Use a proper rated disconnect switch, or de-energize the circuit first (for example, by covering the panels), instead of pulling a loaded connector apart by hand.

Problem 4 [Basic] A cable route needs 6 m across the roof, 2.5 m down the wall, and 0.5 m of slack at each end. Find the total one-way length needed, before adding any spare allowance.

Solution

1. List every segment: 6 m (roof) + 2.5 m (wall) + 0.5 m (slack at one end) + 0.5 m (slack at the other end)
2. Add them together: $6 + 2.5 + 0.5 + 0.5 = 9.5 \text{ m}$

The route needs 9.5 m of cable, before any spare allowance is added.

Problem 5 [Standard] Panel B (Chapter 5, $1.960 \text{ m} \times 0.992 \text{ m}$) will be installed in Duhok, where the recommended tilt is about 37° , mounted with its 1.960 m side running up the slope. Using the minimum spacing factor $k = 2$, find the minimum row-to-row gap.

Solution

1. Find the panel's vertical rise: $\text{rise} = L \times \sin(\beta) = 1.960 \times \sin(37^\circ) \approx 1.960 \times 0.602 \approx 1.18 \text{ m}$
2. Apply the rule of thumb: $D \geq k \times \text{rise} = 2 \times 1.18 \approx 2.36 \text{ m}$
3. Round up for a practical margin: about 2.4 m

The minimum row-to-row gap is about 2.36 m, so plan for at least about 2.4 m.

Problem 6 [Standard] A 24 V system's DC cable was sized for an assumed 6 m one-way run at a 12 A design current, giving a 4 mm² cable for a 3% voltage-drop limit. The real, measured route turned out to be 11 m one-way. (a) Is 4 mm² still large enough? (b) If not, what standard size should be used instead? (Use copper $\rho \approx 0.0175 \Omega \cdot \text{mm}^2/\text{m}$.)

Solution

1. Find the allowed voltage drop: $3\% \times 24 \text{ V} = 0.72 \text{ V}$
2. (a) Check 4 mm² at the real 11 m length: $V_{\text{drop}} = (2 \times 0.0175 \times 11 \times 12) \div 4 = 4.62 \div 4 = 1.155 \text{ V}$
3. (a) As a percentage: $(1.155 \div 24) \times 100 \approx 4.81\%$ — above the 3% limit, so 4 mm² FAILS
4. (b) Find the new minimum cross-section: $A_{\text{min}} = (2 \times 0.0175 \times 11 \times 12) \div 0.72 = 4.62 \div 0.72 \approx 6.42 \text{ mm}^2$
5. (b) Round up to the next standard size: choose 10 mm²

The real 11 m route pushes the voltage drop to about 4.81%, above the 3% limit, so 4 mm² is no longer enough — use 10 mm² instead.

Problem 7 [Standard] A family wants to place their battery bank and inverter inside a small, airtight metal cabinet in direct sun on the roof, to save space and keep it out of sight. List THREE problems with this plan, and suggest a fix for each.

Solution

1. Think about heat: direct sun plus an airtight box traps heat, which shortens battery life and can force electronics to reduce output or shut down.
2. Think about gas: if any flooded lead-acid batteries are used, hydrogen gas has nowhere to escape in a sealed cabinet.
3. Think about access and safety: a small, hot, sealed cabinet is unpleasant and unsafe to open for inspection or repair, and heat plus gas can build up around the worker too, not only the equipment.

Three real problems are trapped heat (shortens life), trapped gas (explosion risk with flooded batteries), and poor access for safe maintenance. Fixes: move it to shade, add proper vent openings (or a fan for a larger bank), and choose a more open, accessible location.

Problem 8 [Standard] An inverter's manual requires 20 cm clearance on each side and 40 cm above. The unit is 45 cm wide and 60 cm tall. Find the minimum wall space (width $\times$ height) to reserve for it.

Solution

1. Width: left clearance + unit width + right clearance = $20 + 45 + 20 = 85 \text{ cm}$
2. Height: unit height + top clearance = $60 + 40 = 100 \text{ cm}$

Reserve at least 85 cm wide by 100 cm tall of clear wall space.

Problem 9 [Standard] A technician sets up a straight ladder to reach a flat roof 4 m above the ground. Using the 4-to-1 rule, how far from the wall should the base of the ladder be placed?

Solution

1. Recall the 4-to-1 rule: for every 4 units of height, move the base out 1 unit
2. Apply it: base distance = height $\div$ 4 = $4 \text{ m} \div 4 = 1 \text{ m}$

The base of the ladder should be set out about 1 m from the wall.

Problem 10 [Challenge] A flat roof is 12 m wide (east–west) by 8 m deep (north–south). Panel A (2.094 m × 1.038 m) will be mounted in tilt frames at 36° in Erbil, portrait orientation (the 2.094 m side running up the north–south slope, and the 1.038 m side facing east–west). Using Lesson 1's minimum row gap of 2.5 m: (a) How many rows fit in the 8 m depth? (b) How many panels fit across the 12 m width in each row? (c) What is the total number of panels, and the total array power in kW?

Solution

1. Find each row's horizontal footprint (projection): footprint = $L \times \cos(\beta) = 2.094 \times \cos(36^\circ) \approx 2.094 \times 0.809 \approx 1.69$ m
2. Find the row-to-row pitch (front edge to front edge): pitch = footprint + gap = 1.69 + 2.5 = 4.19 m
3. (a) Row 1 occupies 0 to 1.69 m. Row 2 starts at 4.19 m and ends at 5.88 m. Row 3 would start at 8.38 m, which is beyond the 8 m roof depth — so only 2 rows fit.
4. (b) Panels per row: $12 \text{ m} \div 1.038 \text{ m} \approx 11.56$, so 11 whole panels fit across each row (ignoring small clamp gaps).
5. (c) Total panels: 2 rows × 11 panels = 22 panels. Total power: $22 \times 450 \text{ W} = 9900 \text{ W} = 9.9 \text{ kW}$

2 rows of 11 panels fit on this roof — 22 panels in total, about 9.9 kW. This is exactly the kind of check the Tilt & Orientation calculator and a real site survey (Chapter 16) confirm before ordering equipment.

Problem 11 [Challenge] During the final walk-through before switching on a new home system, a technician notices: (a) one MC4 connector is not fully clicked together; (b) the earthing wire from the rack is connected but not tight; (c) a battery terminal cover is missing; (d) the array disconnect switch has no label. For EACH finding, say whether it is safe to proceed, and what must be done first.

Solution

1. (a) A half-connected MC4 connector can arc or overheat under load — push it together fully until it clicks, and check it, before proceeding.
2. (b) A loose earthing connection cannot safely carry fault current to the ground — tighten it to the correct torque and re-check, before proceeding.
3. (c) A missing terminal cover leaves a live, high-current terminal exposed to accidental contact or a dropped tool — fit the correct cover before proceeding.
4. (d) An unlabeled disconnect switch is a safety risk during any future emergency or maintenance — label it clearly before considering the checklist complete.

All four findings must be corrected before the system is energized — a commissioning checklist exists exactly to catch small issues like these while they are still easy and safe to fix.

Problem 12 [Challenge] A team must replace one faulty panel in the middle of a 10-panel string ($V_{oc} = 49.5 \text{ V}$ each) on a flat roof at midday in summer. (a) What is the string's approximate total open-circuit voltage? (b) Why is it dangerous to simply unclip the MC4 connectors on either side of the faulty panel while the sun is shining? (c) Describe a safe way to do this job.

Solution

1. (a) In series, voltage adds up: $V_{\text{string}} \approx n \times V_{oc_module} = 10 \times 49.5 \text{ V} = 495 \text{ V}$ — far above household voltage.
2. (b) The string is still 'live' in full sun, even though nothing downstream is switched on. Pulling apart a connector that could be carrying current risks a DC arc, and touching any exposed contact at 495 V is very dangerous.

3. (c) A safe method: cover the string with an opaque sheet to stop light reaching the cells (or work at dawn, dusk, or on a heavily overcast day), open and lock out the relevant disconnects, verify with a rated meter that the section is de-energized, then work using insulated tools and PPE, following the one-hand rule while testing.

The string carries about 495 V in full sun. Never treat a lit string as safe just because it is not wired to anything else — de-energize it as fully as possible (covering it or timing the work), isolate, verify with a meter, and use proper PPE before touching any connector.

CHAPTER EIGHTEEN

Testing and Commissioning

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the main purpose of the testing covered in this chapter?

- A. To sell extra equipment to the customer
- B. To measure a finished system's real performance and confirm it works as designed before regular use begins
- C. To choose the array's size and the battery bank's capacity

Answer: To measure a finished system's real performance and confirm it works as designed before regular use begins. *This chapter tests and confirms a FINISHED system. Choosing sizes is design work (Chapter 12), not commissioning.*

Q2. Voc and Isc should normally be tested with the array already connected to the charge controller and running.

Answer: False. *Voc and Isc are normally tested BEFORE the array is connected to the controller. This is the safest moment, and it confirms the wiring before any power flows.*

Q3. A string's datasheet Voc is 49.0 V. On test day it measures 50.5 V. What is the percent difference, to one decimal place?

Answer: 3.1 % (± 0.3). *Diff = $(50.5 - 49.0) \div 49.0 \times 100 \approx 3.1\%$. A few percent above nameplate is normal on a cool morning, because Voc rises as temperature drops below STC.*

Q4. An array's Isc at standard test conditions is 31.5 A. Using the simple scaling rule, what Isc would you predict at an irradiance of 800 W/m²?

Answer: 25.2 A (± 0.3). *$I_{\text{predicted}} = I_{\text{SC}} \times (G \div G_{\text{STC}}) = 31.5 \times (800 \div 1000) = 25.2 \text{ A}$. Isc scales almost in direct proportion to irradiance.*

Q5. Which of these is the best way to measure a large array's short-circuit current safely?

- A. Connect an ordinary multimeter directly in series without checking its current rating
- B. Use a clamp meter, which measures current without breaking the circuit open
- C. Guess it from the panel's power rating alone

Answer: Use a clamp meter, which measures current without breaking the circuit open. *A clamp meter safely measures higher currents without breaking the circuit or risking a small internal fuse. Always check any meter's current rating before connecting it in series.*

Q6. A battery's voltage measured right after charging stops always shows its true, stable state of charge.

Answer: False. *A reading taken right after charging (or after a heavy load) can be misleadingly high or low. Let the battery rest, with no charging and no load, before reading its resting voltage.*

Q7. Which of these should be checked when testing a battery bank? (Choose all correct answers.)

- A. The bank's total resting voltage
- B. Each individual battery's voltage, not just the total
- C. The voltage while a load is switched on
- D. The color of the battery casing

Answer: The bank's total resting voltage; Each individual battery's voltage, not just the total; The voltage while a load is switched on. Total resting voltage, each battery's own voltage (to catch one weak unit), and voltage under load are all useful checks. Casing color has no electrical meaning.

Q8. A 1.2 kWp array's energy meter shows it produced 4.3 kWh on a day when the plane-of-array irradiation was 5.0 kWh/m². What is the measured performance ratio, as a percentage?

Answer: 71.7 % (± 1.5). $PR = E_{actual} \div (P_{rated} \times H_{POA}) = 4.3 \div (1.2 \times 5.0) = 4.3 \div 6.0 \approx 0.717$, or about 71.7%.

Q9. A system's design performance ratio was 0.80. On commissioning day, the measured PR is 0.72. What is the best next step?

- A. Immediately assume the system is broken and disconnect it
- B. Recognize the gap is worth checking (dust, shading, connections), and consider testing again over more days before deciding
- C. Ignore it — performance ratio does not matter after installation

Answer: Recognize the gap is worth checking (dust, shading, connections), and consider testing again over more days before deciding. A single day's PR can be affected by normal weather noise. A gap of around 10% is worth investigating calmly, and confirming over more days, not an automatic sign of failure.

Q10. A day's plane-of-array irradiation, in kWh/m², is numerically equal to that day's peak sun hours.

Answer: True. Dividing kWh/m² by the reference 1 kW/m² gives the same number, now in hours — the two ideas describe the same quantity, one from Chapter 3's language and one from measurement.

Q11. What is a punch list, in system commissioning?

- A. A list of every tool needed for installation
- B. A written list of items still to finish or fix before final acceptance
- C. A price list for solar equipment

Answer: A written list of items still to finish or fix before final acceptance. A punch list records small remaining tasks or faults found during testing, tracked until they are closed out before final, unconditional acceptance.

Q12. Why should a system's record book be started on commissioning day, not later?

- A. Because the app requires it before it will unlock other features
- B. Because commissioning day's test results become the baseline that every later test is compared against
- C. Because the panels stop working if nothing is written down

Answer: Because commissioning day's test results become the baseline that every later test is compared against. Commissioning results are the system's first, most important record, proving how it performed when new. Later troubleshooting (Chapter 19) and maintenance (Chapter 20) both compare against this baseline.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A panel's datasheet Voc is 45.0 V. A field test measures 46.8 V. Find the percent difference between measured and expected, to one decimal place.

Solution

1. Write the equation: $\text{Diff} = (\text{measured} - \text{expected}) \div \text{expected} \times 100\%$
2. Put in the numbers: $\text{Diff} = (46.8 - 45.0) \div 45.0 \times 100\%$

3. Calculate the top: $46.8 - 45.0 = 1.8$
4. Divide and multiply: $1.8 \div 45.0 \times 100\% = 4.0\%$

The measured Voc is 4.0% higher than expected — a small, normal difference.

Problem 2 [Basic] A module's Isc at standard test conditions is 9.0 A. Find the predicted Isc at an irradiance of 600 W/m^2 .

Solution

1. Write the equation: $I_{\text{predicted}} = I_{\text{SC}} \times (G \div G_{\text{STC}})$
2. Put in the numbers: $I_{\text{predicted}} = 9.0 \text{ A} \times (600 \div 1000)$
3. Calculate: $I_{\text{predicted}} = 9.0 \times 0.6 = 5.4 \text{ A}$

The predicted Isc at 600 W/m^2 is 5.4 A.

Problem 3 [Basic] Using this chapter's typical resting-voltage table for a 12 V lead-acid battery (100% $\approx 12.7 \text{ V}$, 75% $\approx 12.4 \text{ V}$, 50% $\approx 12.2 \text{ V}$, 25% $\approx 12.0 \text{ V}$, 0% $\approx 11.8 \text{ V}$), a technician measures a battery's resting voltage as 12.4 V. What is its approximate state of charge?

Solution

1. Compare the reading, 12.4 V, with the resting-voltage table
2. 12.4 V matches the 75% row exactly

The battery's approximate state of charge is 75%.

Problem 4 [Basic] An off-grid system's controller display shows an operating current of 27.5 A. The array's rated Imp is 30 A. Find the percent difference between the operating current and Imp.

Solution

1. Write the equation: $\text{Diff} = (\text{measured} - \text{expected}) \div \text{expected} \times 100\%$
2. Put in the numbers: $\text{Diff} = (27.5 - 30) \div 30 \times 100\%$
3. Calculate the top: $27.5 - 30 = -2.5$
4. Divide and multiply: $-2.5 \div 30 \times 100\% \approx -8.3\%$

The operating current is about 8.3% below Imp — a normal difference for real, non-STC conditions.

Problem 5 [Standard] A 2.0 kWp array's energy meter shows 7.5 kWh produced in a day when the plane-of-array irradiation was 5.5 kWh/m^2 . (a) Find the measured performance ratio, as a percentage. (b) If the system's design PR was 0.80, is this gap large enough to be worth investigating, using this chapter's rule of thumb?

Solution

1. (a) Write the equation: $\text{PR} = E_{\text{actual}} \div (P_{\text{rated}} \times H_{\text{POA}})$
2. Put in the numbers: $\text{PR} = 7.5 \div (2.0 \times 5.5) = 7.5 \div 11.0 \approx 0.682$, or about 68.2%
3. (b) Gap in percentage points: $80 - 68.2 = 11.8 \text{ points}$
4. Relative gap: $11.8 \div 80 \times 100 \approx 14.8\%$, which falls in the 'worth checking' range (about 5–15%)

Measured PR $\approx 68.2\%$, about 14.8% below the 0.80 design value — worth a calm investigation, not necessarily a serious fault.

Problem 6 [Standard] Over a 30-day month, a 3.5 kWp array's meter shows 500 kWh produced. The month's total plane-of-array irradiation is 180 kWh/m² (an average of 6.0 peak sun hours per day). Find the measured monthly PR, as a percentage.

Solution

1. Write the equation: $PR = E_{\text{actual}} \div (P_{\text{rated}} \times H_{\text{POA}})$
2. Calculate the bottom: $3.5 \times 180 = 630$
3. Divide: $PR = 500 \div 630 \approx 0.794$, or about 79.4%

The measured monthly PR is about 79.4% — inside the normal example range for a healthy system.

Problem 7 [Standard] A 48 V battery bank uses 4 batteries of 12 V each, in series. At rest, three read 12.6 V each and the fourth reads 11.9 V. (a) What is the bank's total resting voltage? (b) Using the resting-voltage table in this chapter, roughly what is the weak battery's state of charge, and what should the commissioning team do?

Solution

1. (a) Add the four resting voltages: $12.6 + 12.6 + 12.6 + 11.9 = 49.7 \text{ V}$
2. (b) Compare 11.9 V with the table: it sits between 12.0 V (25%) and 11.8 V (0%), so roughly 10–15% state of charge
3. The other three batteries, at 12.6 V, are close to full — battery #4 is clearly weaker
4. Add 'battery #4: recheck / retest' to the punch list; recharge it fully and measure again before final acceptance

The bank's total resting voltage is 49.7 V; battery #4 is roughly 10–15% charged and should be added to the punch list for a recheck.

Problem 8 [Standard] An array's I_{sc} at STC is 18.0 A. A clamp meter test is done when an irradiance meter reads 700 W/m², and the clamp meter reads 12.9 A. (a) What I_{sc} would you predict at 700 W/m²? (b) What is the percent difference between the measured and predicted I_{sc}?

Solution

1. (a) $I_{\text{predicted}} = I_{\text{SC}} \times (G \div G_{\text{STC}}) = 18.0 \times (700 \div 1000) = 12.6 \text{ A}$
2. (b) $\text{Diff} = (\text{measured} - \text{expected}) \div \text{expected} \times 100\% = (12.9 - 12.6) \div 12.6 \times 100\%$
3. Calculate: $0.3 \div 12.6 \times 100\% \approx 2.4\%$

The predicted I_{sc} at 700 W/m² is 12.6 A, and the measured 12.9 A is about +2.4% different — a small, normal difference.

Problem 9 [Standard] An array's datasheet gives V_{mp} = 36.0 V and I_{mp} = 11.1 A at STC. While the system runs normally, the controller's display shows an operating voltage of 33.5 V and an operating current of 10.2 A. Find the percent difference for both voltage and current, and state whether this looks normal for a working MPPT system.

Solution

1. Voltage: $\text{Diff} = (33.5 - 36.0) \div 36.0 \times 100\% = -2.5 \div 36.0 \times 100\% \approx -6.9\%$
2. Current: $\text{Diff} = (10.2 - 11.1) \div 11.1 \times 100\% = -0.9 \div 11.1 \times 100\% \approx -8.1\%$

3. Both differences are modest and negative — expected, because real irradiance is almost always below 1000 W/m^2 and real cell temperature is usually above 25°C

4. An MPPT controller continuously seeks the best point for the CURRENT conditions, not the fixed STC-rated point, so operating values a little below V_{mp} and I_{mp} are normal

Voltage is about 6.9% below V_{mp} and current is about 8.1% below I_{mp} — both normal for a healthy, working MPPT system under real, non-STC conditions.

Problem 10 [Challenge] A small rural clinic's off-grid system uses four 350 W panels wired in parallel (array rated power 1.4 kWp; each panel $V_{oc} = 46.0 \text{ V}$, $I_{sc} = 9.8 \text{ A}$), a 48 V battery bank, and a 60 A MPPT controller. During commissioning: (a) Before connecting to the controller, a technician measures the array's V_{oc} as 47.8 V. Find the percent difference from the expected array V_{oc} . (b) An irradiance meter reads 900 W/m^2 during the I_{sc} test; the clamp meter reads 34.9 A. Find the predicted I_{sc} at that irradiance and the percent difference from the measurement. (c) Over the first full day, the plane-of-array irradiation totals 5.8 kWh/m^2 , and the energy meter logs 5.6 kWh delivered to the battery bank. Find the measured PR, as a percentage, and compare it with the clinic's design PR of 0.78.

Solution

1. (a) Wired in parallel, array V_{oc} equals one panel's V_{oc} : expected = 46.0 V. Diff = $(47.8 - 46.0) \div 46.0 \times 100\% \approx 3.9\%$

2. (b) Array I_{sc} at STC (4 panels in parallel): $4 \times 9.8 = 39.2 \text{ A}$. Predicted I_{sc} at 900 W/m^2 : $39.2 \times (900 \div 1000) = 35.28 \text{ A}$

3. Percent difference: $(34.9 - 35.28) \div 35.28 \times 100\% \approx -1.1\%$

4. (c) $PR = E_{\text{actual}} \div (P_{\text{rated}} \times H_{\text{POA}}) = 5.6 \div (1.4 \times 5.8) = 5.6 \div 8.12 \approx 0.690$, or about 69.0%

5. Gap in percentage points: $78 - 69.0 = 9.0$ points. Relative gap: $9.0 \div 78 \times 100 \approx 11.6\%$

V_{oc} is about 3.9% higher than expected (a cool morning, normal); I_{sc} is about 1.1% lower than predicted (normal); the measured PR of about 69.0% is about 11.6% below the 0.78 design PR — inside the 'worth checking' range, not yet a confirmed fault.

Problem 11 [Challenge] A commissioning team collects these results for a small home system (array rated power 1.6 kWp, array I_{sc} at STC = 31.5 A, design PR 0.80): V_{oc} — expected 49.0 V, measured 49.3 V. I_{sc} at 950 W/m^2 — measured 23.4 A. Daily PR — plane-of-array irradiation 5.4 kWh/m^2 , energy delivered 5.5 kWh. (a) Find the percent difference for the V_{oc} reading. (b) Find the predicted I_{sc} at 950 W/m^2 , and the percent difference for the I_{sc} reading. (c) Find the measured PR, as a percentage. (d) Based on all three results, which single reading points most clearly to a real problem, and what kind of fault would you suspect?

Solution

1. (a) Diff(V_{oc}) = $(49.3 - 49.0) \div 49.0 \times 100\% \approx 0.6\%$ — small and normal

2. (b) $I_{\text{predicted}} = 31.5 \times (950 \div 1000) = 29.925 \approx 29.9 \text{ A}$. Diff(I_{sc}) = $(23.4 - 29.9) \div 29.9 \times 100\% \approx -21.8\%$ — a large, abnormal gap

3. (c) $PR = 5.5 \div (1.6 \times 5.4) = 5.5 \div 8.64 \approx 0.637$, or about 63.7% — also clearly below the normal example range

4. (d) Voltage is almost exactly as expected (+0.6%), but current is about 21.8% low. Because voltage is normal, the array's wiring and string configuration are likely correct

5. A current-limiting problem — such as a partly shaded string, heavy dust or soiling, or a loose or corroded connection — fits this pattern better than a wiring mistake, which usually affects voltage too

6. The low daily PR (63.7%) is consistent with this: a current-limiting fault reduces energy production all day, not only at the moment of the Isc test

Voc is normal (+0.6%), but Isc is about 21.8% below predicted and the daily PR is only 63.7% — together these point to a fault that limits CURRENT, such as shading, soiling, or a poor connection, rather than a wiring error.

Problem 12 [Challenge] A telecom relay's 48 V battery bank has four 12 V, 100 Ah batteries in series. Six months after commissioning, a routine record-book check finds these resting voltages: 12.5 V, 12.5 V, 12.6 V, and 11.7 V. (a) Find the bank's total resting voltage. (b) Using this chapter's resting-voltage table, estimate the weak battery's approximate state of charge, and compare it with the others. (c) The site's last full day gave a measured PR of 0.58, well below the site's design PR of 0.80. Is this alone enough to be sure the weak battery is the cause of the low PR? Explain your reasoning. (d) What should go on the punch list, and what should the technician write in the record book?

Solution

1. (a) Add the four resting voltages: $12.5 + 12.5 + 12.6 + 11.7 = 49.3$ V
2. (b) 11.7 V is below the table's lowest listed point, $11.8 \text{ V} \approx 0\%$ — this battery is essentially empty, or possibly has a failing cell, while the other three (12.5–12.6 V) are close to full
3. (c) A low performance ratio compares the array's real energy OUTPUT with the sunlight that reached it — a production-side measurement. A weak battery affects how energy is STORED and delivered, not how much the array produced that day
4. The two problems could be unrelated, or only indirectly linked. The team should investigate the low PR the same way as any other production issue — checking Voc, Isc, shading, dust, and connections on the array side — separately from the battery
5. (d) Punch list item 1: battery #4 reads 11.7 V at rest, well below the others — recharge fully and retest; replace if it stays low. Punch list item 2: investigate the low measured PR (0.58 vs. 0.80 design) as a separate production-side issue
6. Record book: write today's date, all four battery voltages, the measured PR with its irradiation and energy figures, and both new punch list items, so the next technician has the full picture

The bank's total resting voltage is 49.3 V; battery #4 (11.7 V) is essentially empty or failing. The low PR (0.58) is a separate, production-side concern that should not be assumed to have the same cause — both go on the punch list as separate items, and both are recorded in the record book.

CHAPTER NINETEEN

Finding and Fixing Problems

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the correct order of the troubleshooting method taught in this chapter?

- A. Fix → Check → Cause → Symptom
- B. Symptom → Cause → Check → Fix
- C. Cause → Symptom → Fix → Check

Answer: Symptom → Cause → Check → Fix. *You start with what you observe (the symptom), think of possible causes, check them starting with the cheapest and safest, and only then fix the confirmed root cause.*

Q2. You should always replace the most expensive part first when troubleshooting, since it is usually the real cause.

Answer: False. *Guessing and replacing expensive parts first wastes money and does not confirm the real cause. Always check, starting with the cheapest and simplest possibility, before replacing anything.*

Q3. Your solar array produces noticeably less energy than expected on a clear, sunny day. What is usually the FIRST simple thing to check?

- A. Whether the panels need cleaning, or are newly shaded
- B. Whether the panel factory made a manufacturing mistake
- C. Whether the whole array needs to be replaced

Answer: Whether the panels need cleaning, or are newly shaded. *Dust, dirt, and new shading are the most common and cheapest-to-check causes of low production. Check them before assuming equipment failure.*

Q4. Which of these can cause a battery to empty faster than normal? (Choose all correct answers.)

- A. A new parasitic load, like a charger left plugged in
- B. Faster self-discharge in hot weather
- C. A battery bank that was undersized for the current load
- D. Switching from a lead-acid battery to a LiFePO4 battery

Answer: A new parasitic load, like a charger left plugged in; Faster self-discharge in hot weather; A battery bank that was undersized for the current load. *Parasitic loads, faster self-discharge in heat, and an undersized bank are all common causes of a battery emptying faster than expected. Switching to LiFePO4 is not a cause — lithium batteries generally hold their charge better and handle deeper discharge than lead-acid (Chapter 6).*

Q5. An inverter has a standby (parasitic) power draw of 8 W. If it stays powered on all day, every day, how much energy does this waste in one month (30 days), in kWh?

Answer: 5.76 kWh (± 0.05). $E = P \times t = 8 \text{ W} \times 24 \text{ h} \times 30 \text{ days} = 5760 \text{ Wh} = 5.76 \text{ kWh}$. *A small, constant load adds up significantly over a month.*

Q6. A multimeter set to measure current (A) is connected directly across a battery's two terminals by mistake, the way you would measure voltage. What happens?

- A. Nothing happens; the meter simply shows 0 A
- B. The meter may create a short circuit, and can blow its fuse or be damaged

C. The meter automatically switches itself to voltage mode

Answer: The meter may create a short circuit, and can blow its fuse or be damaged. A meter set to current mode has very low internal resistance, because it is designed to sit in series with a circuit. Connecting it in parallel, across a voltage source, creates a near short circuit — a common and avoidable mistake.

Q7. A fully charged 12 V flooded lead-acid battery at rest usually reads about 12.7 V.

Answer: True. This chapter's typical table lists about 12.7 V at rest for a fully charged 12 V lead-acid battery. Real values vary a little by brand and temperature.

Q8. During a voltage-drop test on a live, working connection, which reading suggests a corroded or loose connection?

A. 0.0 V

B. 1.2 V

C. The meter does not matter — only a continuity beep matters

Answer: 1.2 V. A voltage-drop test should read close to 0 V across a good connection. A reading like 1.2 V, well above the 0.5 V guideline, reveals hidden resistance — often a loose or corroded joint.

Q9. Which of these inverter alarms usually means the inverter has detected a wiring or earthing problem, with current leaking to earth?

A. Low battery voltage

B. Overload

C. Ground fault / earth fault

D. Over temperature

Answer: Ground fault / earth fault. A ground fault (or earth fault) alarm means the inverter has detected current finding an unwanted path to earth — often damaged insulation or a wiring mistake. Most inverters shut down automatically to protect people and equipment.

Q10. If you smell burning or see melted insulation near your solar equipment, you should keep testing the system yourself until you find the exact fault, before turning anything off.

Answer: False. Signs of heat damage or burning are a stop sign, not a normal symptom to diagnose. Isolate the system safely if you can do it quickly, keep people away, and call a qualified professional.

Q11. Which situation is the BEST reason to stop and call a qualified professional, instead of continuing DIY troubleshooting?

A. A dusty panel that needs cleaning

B. A loose, cool MC4 connector you can safely reach

C. A suspected arc fault, with a burning smell inside an enclosure

D. A battery that is simply low in the evening, before the next day's charge

Answer: A suspected arc fault, with a burning smell inside an enclosure. A suspected arc fault with a burning smell is a serious fire and safety risk that needs a qualified professional. The other situations are normal, safe parts of routine troubleshooting.

Q12. A 12 V lead-acid battery reads 12.2 V at rest. Using the typical chart from this chapter, about what state of charge does this suggest?

Answer: 50 % (± 10). This chapter's typical table lists about 12.2 V at rest as roughly 50% state of charge for a 12 V lead-acid battery.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] On a clear, sunny afternoon, a home's solar array makes noticeably less power than it did last month. No new shade (trees, buildings) has appeared, and nothing else in the system has changed — except that the panels have not been cleaned in three months, during the dry season. (a) What is the most likely cause? (b) What simple check would help confirm it? (c) What is the fix?

Solution

1. Look at Lesson 2's low-daytime-production table: dust/soiling is the simplest, most common, and cheapest cause to check.
2. The clues point away from shading (no new shade) and away from a wiring fault (nothing else changed) — dust fits every clue given.
3. Confirm with a simple check: look at the panels, or clean one panel and compare its output with an uncleaned one.
4. If cleaning restores the output, dust was the root cause; if not, move on to the next row of the table.

The most likely cause is dust/soiling on the panels; cleaning them (Chapter 20) is the expected fix.

Problem 2 [Basic] A family's off-grid battery used to last all night. This week, without any big new appliance added, it is nearly empty every morning. The only change: their son now leaves his laptop charger plugged into an inverter outlet all day and night, even when the laptop itself is not connected. (a) What is this kind of small, always-on drain called? (b) What is the simple, no-cost fix?

Solution

1. Notice the pattern: no big new appliance was added, but the drain increased — this points toward something small running continuously, not something large running briefly.
2. A charger left plugged in, even with nothing charging, can still draw a small current all day and night — this is called a parasitic load.
3. The fix costs nothing: unplug chargers and similar devices when they are not actively charging something.

The likely cause is a parasitic load (the always-plugged-in charger); the fix is simply to unplug it when it is not in use.

Problem 3 [Basic] While checking a solar array on a warm afternoon, a technician notices that one MC4 connector feels noticeably warmer than the others nearby, with a small white-green crust visible where the metal pins meet. (a) What is this crust most likely to be? (b) Why is a warm connector a warning sign, not just a curiosity? (c) What should the technician do?

Solution

1. Match the clues to Lesson 2's connections table: a warm MC4 connector with visible crust is a classic corrosion symptom.
2. Recall Ohm's law: extra resistance at a joint, with current still flowing through it, wastes power as heat ($P = I^2 \times R$) — this is why it feels warm.
3. Decide the fix: never leave a warm, corroded connector in service — isolate the circuit safely, then clean or replace the connector.

The crust is corrosion; the warmth shows wasted power turning into heat at a resistant joint, which should be fixed before it gets worse.

Problem 4 [Basic] A technician wants to check whether a fuse has 'blown' (broken inside), using the multimeter's continuity/resistance setting, while the circuit is currently switched on and powered. Is it safe to test the fuse like this right now? What should be done instead?

Solution

1. Recall the multimeter tests table in Lesson 3: the continuity test needs the circuit's power OFF.
2. Testing continuity on a live, powered circuit can give a false or confusing reading, and can damage the meter.
3. Correct order: isolate the circuit at a proper disconnect switch (Chapter 9), confirm it is de-energized, then run the continuity test on the fuse.

It is not safe to continuity-test a live circuit; isolate the circuit first, then test.

Problem 5 [Standard] An off-grid inverter displays a 'Ground Fault' alarm and refuses to power the loads. (a) What does this alarm generally mean? (b) Name two realistic things a technician should check. (c) What must the technician do before touching any wiring to check it?

Solution

1. Match the alarm to Lesson 2's inverter alarms table: 'ground fault / earth fault' means current is finding an unwanted path to earth.
2. List realistic causes: damaged insulation touching metal, moisture inside an enclosure or connector, or an earthing/wiring mistake.
3. Apply the chapter's safety rule: a real ground fault can mean dangerous voltage on normally-safe metal parts, so isolate and confirm de-energized before any hands-on check.

A ground fault alarm means leakage current to earth; check for damaged insulation, moisture, or wiring mistakes — but isolate the system safely first.

Problem 6 [Standard] A technician measures a 12 V flooded lead-acid battery at rest (no charging, no load, for 2 hours) and reads 12.0 V. Using the typical chart in Lesson 3, about what state of charge does this suggest? Should the technician be concerned yet?

Solution

1. Compare 12.0 V with the typical 12 V lead-acid table in Lesson 3.
2. 12.0 V lines up with about 25% state of charge.
3. 25% is low for a lead-acid battery; deep, repeated discharge below this level shortens battery life (Chapter 6), so it is worth investigating further, not ignoring.

About 25% state of charge — low enough to investigate, and worth re-checking after a full charge.

Problem 7 [Standard] While a 12 V off-grid system is running with 8 A flowing, a technician measures a voltage drop of 0.6 V across one suspect MC4 connector, using the voltage-drop test. (a) What is the resistance of this connector? (b) How much power is it wasting as heat?

Solution

1. Write Ohm's law rearranged for resistance: $R = V \div I$
2. Put in the numbers: $R = 0.6 \text{ V} \div 8 \text{ A} = 0.075 \Omega$
3. Find the wasted power: $P = V \times I = 0.6 \text{ V} \times 8 \text{ A} = 4.8 \text{ W}$

4. Compare with the chapter's rule of thumb: above about 0.5 V at one connection is worth fixing — 0.6 V is just over that line.

The connector has about 0.075 Ω of hidden resistance and is wasting 4.8 W as heat — enough to feel warm, and worth cleaning or replacing.

Problem 8 [Standard] An inverter's standby (parasitic) draw is 7 W, and it stays powered on 24 hours a day, every day. (a) How much energy does this waste in one month (30 days), in kWh? (b) At an example price of 100 IQD per kWh (as used in Chapter 1), how much does this cost per month? (c) How much per year (365 days)?

Solution

1. Daily energy: $E = P \times t = 7 \text{ W} \times 24 \text{ h} = 168 \text{ Wh} = 0.168 \text{ kWh}$
2. Monthly energy: $0.168 \text{ kWh} \times 30 = 5.04 \text{ kWh}$
3. Monthly cost: $5.04 \text{ kWh} \times 100 \text{ IQD/kWh} = 504 \text{ IQD}$ (example price)
4. Yearly energy: $0.168 \text{ kWh} \times 365 = 61.32 \text{ kWh}$; yearly cost: $61.32 \times 100 \approx 6,132 \text{ IQD}$ (example price)

About 5.04 kWh and 504 IQD wasted per month, or about 6,132 IQD per year at this example price — small loads add up over a whole year.

Problem 9 [Standard] A home's solar system was commissioned with an expected output of 12 kWh per day in summer (Chapter 18). This week, a technician measures actual output of 7.2 kWh on a similar clear, sunny day. (a) What percentage of expected output is the system producing? (b) Is this within the normal 80–95% day-to-day range, or does it point to a real fault? (c) Name two likely causes to check first.

Solution

1. Write the equation: $R_{\text{output}} = (E_{\text{actual}} \div E_{\text{expected}}) \times 100$
 2. Put in the numbers: $R_{\text{output}} = (7.2 \div 12) \times 100$
 3. Calculate: $R_{\text{output}} = 60\%$
 4. Compare with the normal 80–95% range from Lesson 2: 60% is well below it, so this is a fault, not normal weather variation.
 5. Check the low-production table first for the simplest causes: dust, shading, or a failed part of the array.
- 60% of expected output — clearly below the normal range, so this needs investigation, starting with dust, shading, and a check of each string.**

Problem 10 [Challenge] A shop in Erbil has a small off-grid solar system. This month the owner reports two problems together: (1) the array produces less energy than usual on sunny days, and (2) the battery is empty earlier each night. A site visit finds a thin layer of dust on the panels, AND a new neighboring building now shades one corner of the array from about 3 p.m. onward. (a) Explain how these two site findings could cause BOTH symptoms. (b) List the findings using the method: symptom → possible causes → check → fix. (c) Which of the two fixes is simpler, and why?

Solution

1. Recall Chapter 5: shading and soiling both reduce array output, and shading effects can be larger than the shaded area alone because of how strings behave.
2. Connect the chain: less array output during the day → less charging → the battery starts the evening at a

lower state of charge → it runs out earlier at night. Two symptoms, one shared cause.

3. Apply the method in order: symptom = low production and early-empty battery; possible causes = dust, new shading, a wiring/string fault, an aging battery; check = inspect panels for dust, watch the array through the afternoon for shadows, compare string outputs, check battery age and resting-voltage trend; fix = clean the panels, and address the shading.

4. Compare the two fixes: cleaning is fast and cheap; shading often needs a bigger, sometimes permanent, decision.

Both the dust and the new shading reduce daytime output, which explains both the low production AND the earlier-empty battery; cleaning is the simpler fix, while the shading problem needs a bigger decision.

Problem 11 [Challenge] During a voltage-drop test on a battery interconnect cable carrying 25 A, a technician measures 1.5 V across a single connector. (a) Calculate the connector's resistance and the power it is wasting as heat. (b) This chapter's rule of thumb flags voltage drops above about 0.5 V at one connection. Is this reading a serious concern? (c) The connector is too hot to touch comfortably, and there is a faint smell of hot plastic. What should the technician do right now, and why might this now need a qualified professional rather than a simple fix?

Solution

1. Write Ohm's law rearranged: $R = V \div I = 1.5 \text{ V} \div 25 \text{ A} = 0.06 \Omega$

2. Find the wasted power: $P = V \times I = 1.5 \text{ V} \times 25 \text{ A} = 37.5 \text{ W}$ (matches $P = I^2 \times R = 25^2 \times 0.06 = 37.5 \text{ W}$)

3. Compare with the 0.5 V guideline from Lesson 3: 1.5 V is three times higher — a serious warning, not a minor one.

4. Apply the Lesson 4 decision table: heat damage and a burning smell are signs to isolate immediately and consider calling a qualified professional, rather than continuing to test or simply reconnecting.

The connector has about 0.06 Ω resistance, wasting 37.5 W as heat — a serious, three-times-over-guideline reading with signs of heat damage, so the system should be isolated immediately and a qualified professional may be needed.

Problem 12 [Challenge] A family's off-grid home system was commissioned one year ago with an expected daily output of 10 kWh on a clear summer day (Chapter 18). This month a technician finds: (1) actual output on a similar clear day is 8.5 kWh; (2) the battery bank (nominal 24 V, 200 Ah) reads 25.0 V at rest one morning after a full day of good sun the day before; and (3) one battery interconnection cable feels slightly warm, with a 0.4 V drop across it while 15 A was flowing. (a) What percentage of expected output is the system achieving — is this normal? (b) A 24 V bank behaves like two 12 V batteries in series. Using the 12 V table from Lesson 3 (scaled $\times 2$), is the 25.0 V morning reading normal? (c) Calculate the resistance and power wasted at the warm interconnection. (d) Overall, does this system need urgent professional attention, or can it be handled with routine care? Use (a)–(c) to justify your answer.

Solution

1. Production check: $\% = (8.5 \div 10) \times 100\% = 85\%$, which is inside the normal 80–95% range from Lesson 2.

2. Battery check: scale the 12 V table $\times 2$ for a 24 V bank — $12.4 \text{ V} \times 2 = 24.8 \text{ V}$ (75%) and $12.7 \text{ V} \times 2 = 25.4 \text{ V}$ (100%). 25.0 V sits between these, closer to the top — roughly 80–85% state of charge, which is normal the morning after a full day of good sun.

3. Connection check: $R = V \div I = 0.4 \div 15 \approx 0.027 \Omega$; $P = V \times I = 0.4 \times 15 = 6 \text{ W}$.

4. Compare with Problem 11's dangerous case (1.5 V, 37.5 W, burning smell): this joint's 0.4 V and 6 W,

with no burning smell or serious heat, is a much smaller, routine concern.

5. Conclusion: all three checks are normal or minor — routine care (clean and tighten the warm joint) is enough; this is not an urgent, professional-only situation.

Production (85%) and battery voltage (about 80–85% state of charge) are both normal, and the warm joint (6 W) is a minor finding — routine maintenance is enough; this system does not need urgent professional attention.

CHAPTER TWENTY

Maintenance

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. What is the main difference between preventive and corrective maintenance?

- A. Preventive maintenance is planned and regular; corrective maintenance happens after something has already gone wrong
- B. Preventive maintenance is only for batteries; corrective maintenance is only for solar panels
- C. There is no real difference — the two words mean the same thing

Answer: Preventive maintenance is planned and regular; corrective maintenance happens after something has already gone wrong. *Preventive maintenance is done on a schedule, before a problem happens — like cleaning panels regularly. Corrective maintenance is repair work done after something has already failed.*

Q2. Soiling (dust on a panel) causes the same kind of permanent damage as panel degradation.

Answer: False. *Soiling is temporary and fully reversible — a good cleaning brings the power back. Degradation is the slow, permanent aging of a panel's materials over many years, and cleaning cannot fix it.*

Q3. A 2 kW array has a soiling loss of 15% before cleaning and 3% right after cleaning. The site's example peak sun hours are 6 hours per day. How much extra energy (in kWh) does cleaning gain in one day?

Answer: 1.44 kWh (± 0.05). *Before cleaning: $2 \text{ kW} \times (1 - 0.15) \times 6 \text{ h} = 10.2 \text{ kWh}$. After cleaning: $2 \text{ kW} \times (1 - 0.03) \times 6 \text{ h} = 11.64 \text{ kWh}$. The gain is $11.64 - 10.2 = 1.44 \text{ kWh}$ for that one day.*

Q4. Which tool measures the specific gravity of a flooded lead-acid battery's electrolyte?

- A. Multimeter
- B. Hydrometer
- C. Thermometer

Answer: Hydrometer. *A hydrometer measures the density (specific gravity) of the electrolyte, which shows the battery's state of charge. A multimeter measures voltage, current, and resistance (Chapter 2); a thermometer measures temperature.*

Q5. Which of these are things a technician should look for during a visual inspection of a solar array? (Choose all correct answers.)

- A. Cracked glass on a panel
- B. A comfortable outdoor temperature
- C. Corrosion or a greenish powder on a connection
- D. Loose or rusted mounting bolts

Answer: Cracked glass on a panel; Corrosion or a greenish powder on a connection; Loose or rusted mounting bolts. *Cracked glass, corrosion at connections, and loose or rusted mounting hardware are all real warning signs to check for. A comfortable outdoor temperature is not itself a fault to look for during a visual inspection.*

Q6. You should top up a flooded lead-acid battery's low electrolyte with ordinary tap water.

Answer: False. *Always use distilled (de-ionized) water. Tap water contains minerals that can damage the battery's cells over time.*

Q7. In this chapter's yearly maintenance budget equation, the maintenance reserve is calculated as...

- A. System capital cost $\times$ maintenance rate
- B. System capital cost $\div$ maintenance rate
- C. System capital cost $-$ maintenance rate

Answer: System capital cost $\times$ maintenance rate. $C_{\text{reserve}} = C_{\text{capital}} \times r_{\text{maint}}$. For example, a system worth 10,000,000 IQD with a 2% rate sets aside 200,000 IQD a year.

Q8. A shop's solar system has an example capital cost of 8,000,000 IQD. The owner plans a 2.5% annual maintenance reserve. What is the yearly reserve, in IQD?

Answer: 200000 IQD ($\pm$ 2000). $C_{\text{reserve}} = C_{\text{capital}} \times r_{\text{maint}} = 8,000,000 \times 0.025 = 200,000$ IQD.

Q9. In most of Iraq and the Kurdistan Region, which season usually needs the MOST frequent solar panel cleaning?

- A. Winter (rain, low sun)
- B. Spring and summer (dust storms, dry heat)
- C. Cleaning needs are the same all year

Answer: Spring and summer (dust storms, dry heat). Chapter 5 and this chapter both describe spring through summer as the region's dust season, with dust storms and fast dust buildup — this is when panels need cleaning most often.

Q10. Which of these care tasks apply specifically to FLOODED lead-acid batteries? (Choose all correct answers.)

- A. Check and top up electrolyte level with distilled water
- B. Rely only on a battery management system (BMS) for protection
- C. Check specific gravity with a hydrometer
- D. Keep the area well ventilated because of hydrogen gas

Answer: Check and top up electrolyte level with distilled water; Check specific gravity with a hydrometer; Keep the area well ventilated because of hydrogen gas. Electrolyte level, specific gravity, and ventilation for hydrogen gas are all flooded-battery tasks. Relying on a BMS is how LiFePO₄ (lithium) batteries are protected, not flooded lead-acid ones (Chapter 6).

Q11. A maintenance log is only useful for legal or warranty reasons, not for finding problems early.

Answer: False. A log kept over time can show a pattern — like a battery needing water top-ups more and more often — that no single visit would reveal on its own. This is one of a log's most valuable uses.

Q12. A technician plans a full visual inspection every 8 weeks. About how many inspections happen in one year (52 weeks)? Round to a whole number, rounding up.

Answer: 7 inspections ($\pm$ 0.1). $52 \div 8 = 6.5$. Round UP to 7, so that no gap between inspections is ever longer than the planned 8 weeks.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A 5 kW array has a soiling loss of 10% during a dusty week. What is its actual power output in strong, direct sunlight?

Solution

1. Write the equation: $P_{\text{actual}} = P_{\text{STC}} \times (1 - L_{\text{soil}})$
2. Change the percent to a fraction: $10\% = 0.10$
3. Put in the numbers: $P_{\text{actual}} = 5 \text{ kW} \times (1 - 0.10) = 5 \times 0.90$

4. Calculate: $P_{\text{actual}} = 4.5 \text{ kW}$

The array's actual power output is 4.5 kW.

Problem 2 [Basic] A hydrometer reading on a flooded battery bank corresponds to 80% state of charge (SoC). What is its depth of discharge (DoD)?

Solution

1. Recall from Chapter 6: $\text{DoD} = 100\% - \text{SoC}$
2. Put in the numbers: $\text{DoD} = 100\% - 80\%$
3. Calculate: $\text{DoD} = 20\%$

The battery bank's depth of discharge is 20%.

Problem 3 [Basic] A solar system has an example capital cost of 10,000,000 IQD. The owner plans a 1% annual maintenance reserve. Find the yearly reserve.

Solution

1. Write the equation: $C_{\text{reserve}} = C_{\text{capital}} \times r_{\text{maint}}$
2. Change the percent to a fraction: $1\% = 0.01$
3. Put in the numbers: $C_{\text{reserve}} = 10,000,000 \times 0.01$
4. Calculate: $C_{\text{reserve}} = 100,000 \text{ IQD}$

The yearly maintenance reserve is 100,000 IQD.

Problem 4 [Basic] A technician inspects a system every 4 weeks. About how many inspections happen in one year (52 weeks)?

Solution

1. Weeks in a year: 52
2. Divide by the interval: $52 \div 4 = 13$
3. This divides evenly, so no rounding is needed

13 inspections happen in one year.

Problem 5 [Standard] A 4 kW array has a soiling loss of 12% before cleaning and 4% right after cleaning. The site's example peak sun hours are 6.5 hours per day. Find the extra energy cleaning gains in one day.

Solution

1. Before cleaning: $P_{\text{actual}} = 4 \text{ kW} \times (1 - 0.12) = 4 \times 0.88 = 3.52 \text{ kW}$
2. Energy before: $E = 3.52 \text{ kW} \times 6.5 \text{ h} = 22.88 \text{ kWh}$
3. After cleaning: $P_{\text{actual}} = 4 \text{ kW} \times (1 - 0.04) = 4 \times 0.96 = 3.84 \text{ kW}$
4. Energy after: $E = 3.84 \text{ kW} \times 6.5 \text{ h} = 24.96 \text{ kWh}$
5. Energy gained: $24.96 - 22.88 = 2.08 \text{ kWh}$

Cleaning gains about 2.08 kWh on that one day.

Problem 6 [Standard] A 6 kW rooftop array goes six weeks without cleaning during the dust season and reaches an 18% soiling loss (Chapter 5's 'heavy dust' range). Right after cleaning, the loss drops to 3%. The site's example peak sun hours are 7 hours per day. Find the energy lost to dust in one 30-day month, comparing the dusty condition with the freshly cleaned condition.

Solution

1. Dusty power: $P_{\text{actual}} = 6 \text{ kW} \times (1 - 0.18) = 6 \times 0.82 = 4.92 \text{ kW}$
2. Dusty energy for the month: $E = 4.92 \text{ kW} \times 7 \text{ h} \times 30 \text{ days} = 1033.2 \text{ kWh}$
3. Clean power: $P_{\text{actual}} = 6 \text{ kW} \times (1 - 0.03) = 6 \times 0.97 = 5.82 \text{ kW}$
4. Clean energy for the month: $E = 5.82 \text{ kW} \times 7 \text{ h} \times 30 \text{ days} = 1222.2 \text{ kWh}$
5. Energy lost to dust: $1222.2 - 1033.2 = 189 \text{ kWh}$

The array loses about 189 kWh that month because of dust — energy that a proper cleaning schedule would have kept.

Problem 7 [Standard] A 12 V, 600 Ah flooded lead-acid battery bank has a maximum safe depth of discharge of 50%. A hydrometer check shows the bank is at 65% state of charge. How much more energy, in Wh, can safely be drawn before the bank reaches its 50% DoD limit?

Solution

1. Find the current DoD: $\text{DoD}_{\text{now}} = 100\% - \text{SoC} = 100\% - 65\% = 35\%$
2. Find the remaining safe DoD: $50\% - 35\% = 15\%$ (as a fraction, 0.15)
3. Use Chapter 6's usable-energy equation: $E_{\text{remaining}} = V \times C \times \text{DoD}$
4. Put in the numbers: $E_{\text{remaining}} = 12 \text{ V} \times 600 \text{ Ah} \times 0.15$
5. Calculate: $E_{\text{remaining}} = 1080 \text{ Wh}$

1080 Wh (1.08 kWh) can still safely be drawn before the bank reaches its 50% DoD limit.

Problem 8 [Standard] A home system has an example capital cost of 15,000,000 IQD. The owner sets aside a 2% annual maintenance reserve, plus example routine costs of 250,000 IQD per year for cleaning materials and an annual inspection visit. Find the total yearly maintenance budget.

Solution

1. Annual maintenance reserve: $C_{\text{reserve}} = C_{\text{capital}} \times r_{\text{maint}} = 15,000,000 \times 0.02 = 300,000 \text{ IQD}$
2. Routine yearly cost (given): $C_{\text{routine}} = 250,000 \text{ IQD}$
3. Total yearly maintenance budget: $B_{\text{annual}} = C_{\text{reserve}} + C_{\text{routine}} = 300,000 + 250,000 = 550,000 \text{ IQD}$

The total yearly maintenance budget is 550,000 IQD.

Problem 9 [Standard] Two identical 4 kW systems sit in the same location, with the same example 6 peak sun hours per day. System A is cleaned regularly and has only a 4% soiling loss. System B is neglected and has a 20% soiling loss. Find the difference in their daily energy production.

Solution

1. System A power: $4 \text{ kW} \times (1 - 0.04) = 4 \times 0.96 = 3.84 \text{ kW}$; energy: $3.84 \times 6 = 23.04 \text{ kWh/day}$
2. System B power: $4 \text{ kW} \times (1 - 0.20) = 4 \times 0.80 = 3.2 \text{ kW}$; energy: $3.2 \times 6 = 19.2 \text{ kWh/day}$
3. Difference: $23.04 - 19.2 = 3.84 \text{ kWh/day}$

System A produces about 3.84 kWh per day more than neglected System B — purely because of dust.

Problem 10 [Challenge] A shop's 5 kW rooftop array is neglected for a full dusty-season month and reaches a 20% soiling loss (Chapter 5's 'heavy dust' range), compared with a 3% loss right after cleaning. The site's example peak sun hours are 7 hours per day, over a 30-day month. The example electricity value is 100 IQD/kWh (Chapter 1). (a) Find the energy lost to dust that month. (b) Find the money value of that lost energy. (c) A professional cleaning costs an example 40,000 IQD. Based on ONE month's loss alone, did the cleaning pay for itself, and by how much?

Solution

1. Dusty power: $5 \text{ kW} \times (1 - 0.20) = 4.0 \text{ kW}$; monthly energy: $4.0 \times 7 \times 30 = 840 \text{ kWh}$
2. Clean power: $5 \text{ kW} \times (1 - 0.03) = 4.85 \text{ kW}$; monthly energy: $4.85 \times 7 \times 30 = 1018.5 \text{ kWh}$
3. (a) Energy lost to dust: $1018.5 - 840 = 178.5 \text{ kWh}$
4. (b) Money value: $178.5 \text{ kWh} \times 100 \text{ IQD/kWh} = 17,850 \text{ IQD}$
5. (c) Compare with the cleaning cost: $17,850 \text{ IQD} < 40,000 \text{ IQD}$, a shortfall of $40,000 - 17,850 = 22,150 \text{ IQD}$

In a single month, the dust cost the shop 178.5 kWh (17,850 IQD) — less than the 40,000 IQD cleaning cost by itself. But a cleaning visit protects several months of production, not just one, and often includes a wider inspection too, so regular cleaning is still usually worthwhile over a longer time — this is why Lesson 4's yearly budget plans for cleaning as a routine cost, not a one-time decision.

Problem 11 [Challenge] A 12 V, 800 Ah flooded lead-acid battery bank has a maximum safe depth of discharge of 50%. A technician's maintenance log shows that, for about the same daily load, the bank reached its 50% DoD limit after an average of 4 days in month 1, but after only an average of 3 days by month 6. (a) Find the bank's usable energy between full charge and the 50% DoD limit. (b) Using month 1's figure, roughly what was the daily energy draw? (c) What does the change from 4 days to 3 days most likely suggest, and what should the technician do?

Solution

1. (a) Usable energy: $E_{\text{usable}} = V \times C \times \text{DoD} = 12 \text{ V} \times 800 \text{ Ah} \times 0.50 = 4800 \text{ Wh}$
 2. (b) If about 4800 Wh was used over 4 days, the daily draw $\approx 4800 \div 4 = 1200 \text{ Wh/day}$
 3. (c) For roughly the same daily load, the bank now empties to the 50% DoD limit in 3 days instead of 4 — it is delivering less usable energy for the same use than before
- (a) 4800 Wh, (b) about 1200 Wh/day, (c) The battery bank is most likely losing usable capacity — a common sign of aging (Chapter 6). The technician should first check that the charge controller's voltage settings are correct (Chapter 7), and then plan and budget for likely battery replacement soon (Lesson 4), before a sudden failure happens.**

Problem 12 [Challenge] A family's off-grid home system has an example capital cost of 20,000,000 IQD. They plan a 1.5% annual maintenance reserve, plus example routine costs of 400,000 IQD per year. (a) Find their total annual maintenance budget. (b) Express this as a monthly figure. (c) During the four-month dusty season, professional cleaning costs an example 15,000 IQD per visit, once a month. Does their planned monthly maintenance budget comfortably cover this cleaning cost?

Solution

1. Annual maintenance reserve: $C_{\text{reserve}} = 20,000,000 \times 0.015 = 300,000 \text{ IQD}$

2. (a) Total annual budget: $B_{\text{annual}} = C_{\text{reserve}} + C_{\text{routine}} = 300,000 + 400,000 = 700,000$ IQD
 3. (b) Monthly figure: $700,000 \div 12 \approx 58,333$ IQD/month
 4. (c) Compare with the cleaning cost: 15,000 IQD is much less than 58,333 IQD/month, leaving about $58,333 - 15,000 \approx 43,333$ IQD for other maintenance tasks that month
- (a) 700,000 IQD per year, (b) about 58,333 IQD per month, (c) Yes — the monthly budget comfortably covers a 15,000 IQD cleaning visit, with roughly 43,333 IQD left over for other tasks.**

CHAPTER TWENTY-ONE

Solar Energy in Iraq and the Kurdistan Region

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. Which statement best describes the solar resource across Iraq and the Kurdistan Region?

- A. It is generally low compared to most of the world
- B. It is generally strong, similar to much of the Middle East — though the exact city-by-city numbers in this chapter are illustrative examples
- C. It is only strong in winter

Answer: It is generally strong, similar to much of the Middle East — though the exact city-by-city numbers in this chapter are illustrative examples. *The region sits in a latitude band with a generally strong, well-known solar resource. However, this chapter's specific city numbers are clearly labeled examples for practice, not verified measurements.*

Q2. The peak-sun-hour numbers given for each city in this chapter are confirmed, precisely measured local data.

Answer: False. *They are clearly labeled illustrative examples for practice. Verified, sourced regional data collection is a separate future task for this project.*

Q3. Using this chapter's example value of 5.3 peak sun hours per day for Erbil and an example performance ratio of 0.80, how much energy would a 2 kW array produce in one day, in kWh?

Answer: 8.48 kWh (± 0.05). $E = P \times PSH \times PR = 2 \text{ kW} \times 5.3 \text{ h} \times 0.80 = 8.48 \text{ kWh}$. *This is the same method as the Lesson 1 worked example, with a 2 kW array instead of 3 kW.*

Q4. What is the main reason summer heat reduces a solar panel's power output?

- A. A higher cell temperature reduces the panel's power a little, following its temperature coefficient
- B. Panels completely stop working above 25°C
- C. Heat increases a panel's efficiency

Answer: A higher cell temperature reduces the panel's power a little, following its temperature coefficient. *Every crystalline silicon panel has a temperature coefficient — it loses a small percentage of power for every degree above its 25°C test condition. Lesson 2's worked example shows this can be significant on a hot regional summer day.*

Q5. Which of these are typical local reasons homes and businesses want solar-plus-battery systems? (Choose all correct answers.)

- A. Limited national grid hours
- B. Expensive neighborhood generator subscriptions
- C. Solar panels work better at night
- D. Reducing generator noise and diesel fumes

Answer: Limited national grid hours; Expensive neighborhood generator subscriptions; Reducing generator noise and diesel fumes. *Limited grid hours, costly generator subscriptions, and reducing noise and fumes are all real local motivations. Solar panels need daylight — they do not work better, or at all, at night.*

Q6. Dust and haze can reduce the sunlight reaching a solar panel, so regular cleaning is part of maintenance in this region.

Answer: True. Dust and haze block some sunlight before it reaches the solar cells. A regular cleaning schedule (Chapter 20), especially in dusty seasons, helps recover lost output.

Q7. Which system type is generally the most common local fit for a home or business with a grid connection that is not available all day, plus a neighborhood generator?

- A. A pure grid-tied (on-grid) system with no battery
- B. A hybrid system with a battery, able to use grid, generator, and solar power
- C. A system with no battery and no grid connection at all

Answer: A hybrid system with a battery, able to use grid, generator, and solar power. A hybrid system with a battery can store solar energy and use grid or generator power when needed — the best fit for a grid that is not available all day, the common regional situation described in Lesson 2.

Q8. This chapter's example price range for lithium batteries is \$250 to \$450 per kWh of capacity. What is the midpoint example price, in USD per kWh?

Answer: 350 USD/kWh (± 5). Midpoint = $(250 + 450) \div 2 = \$350$ per kWh. Remember this is only an illustrative example range, not a confirmed current market price.

Q9. What does 'balance of system' (BOS) refer to?

- A. Only the solar panels
- B. Everything except the panels, batteries, controller, and inverter — for example, mounting, cables, and breakers
- C. The total cost of the whole system, including every part

Answer: Everything except the panels, batteries, controller, and inverter — for example, mounting, cables, and breakers. Balance of system means all the supporting parts — mounting frames, cables, connectors, and breakers — not the main panels, battery, controller, or inverter, and not the total system cost.

Q10. A system costs an example 4,000,000 IQD and saves its owner an example 2,000,000 IQD per year. What is the simple payback period, in years?

Answer: 2 years (± 0.1). Payback = System cost $\div$ Annual savings = $4,000,000 \div 2,000,000 = 2$ years.

Q11. Local rules about permits, grid connection, and safety requirements are exactly the same everywhere in Iraq and the Kurdistan Region, and never change.

Answer: False. Rules can differ between governorates and cities, and can change over time. Always confirm current requirements locally before a real project.

Q12. Which best describes the case studies in Lesson 5?

- A. Exact records of specific, named, verified real installations
- B. Illustrative composite examples, representative of common project types, not citations of specific verified projects
- C. Data collected from an official government survey

Answer: Illustrative composite examples, representative of common project types, not citations of specific verified projects. Lesson 5 states clearly that its case studies are illustrative composites built from common patterns, not citations of specific real, verified projects.

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] This chapter's example summer peak sun hours for Sulaymaniyah are about 7.0–7.5 h/day. Find the midpoint of this range, and find the energy a 1 kW array would produce in one day at that midpoint, ignoring all losses (performance ratio = 1, for this simple practice question).

Solution

1. Find the midpoint: $(7.0 + 7.5) \div 2 = 7.25$ h/day
2. Write the equation: $E = P \times \text{PSH} \times \text{PR}$
3. Put in the numbers: $E = 1 \text{ kW} \times 7.25 \text{ h} \times 1 = 7.25 \text{ kWh}$

The example midpoint is 7.25 h/day, so a 1 kW array would produce about 7.25 kWh that day, ignoring losses.

Problem 2 [Basic] This chapter uses an example exchange rate of 1 USD $\approx$ 1,310 IQD. Convert an example solar panel price of \$0.30 per watt into IQD per watt.

Solution

1. Write the conversion: price in IQD/W = price in USD/W $\times$ exchange rate
2. Put in the numbers: $0.30 \times 1,310$
3. Calculate: 393 IQD/W

\$0.30 per watt is about 393 IQD per watt, using this chapter's example exchange rate.

Problem 3 [Basic] A shop uses: 4 LED lamps (10 W each) for 10 hours, a small refrigerator (120 W) running effectively 8 hours, and a fan (60 W) for 10 hours during opening hours. Find the shop's daily energy use, in kWh.

Solution

1. Lamps: $4 \times 10 \text{ W} = 40 \text{ W}$; $E = 40 \times 10 \text{ h} = 400 \text{ Wh}$
2. Refrigerator: $E = 120 \text{ W} \times 8 \text{ h} = 960 \text{ Wh}$
3. Fan: $E = 60 \text{ W} \times 10 \text{ h} = 600 \text{ Wh}$
4. Total: $400 + 960 + 600 = 1,960 \text{ Wh} = 1.96 \text{ kWh}$

The shop uses about 1.96 kWh per day.

Problem 4 [Basic] A panel is rated 300 W at 25°C. Using an example temperature coefficient of -0.4% per °C, estimate its power output when its cell temperature reaches 55°C.

Solution

1. Find the temperature rise: $\Delta T = 55^\circ\text{C} - 25^\circ\text{C} = 30^\circ\text{C}$
2. Find the percentage loss: $0.4\% \times 30 = 12\%$
3. Apply the loss: Output = $300 \text{ W} \times (1 - 0.12) = 300 \times 0.88 = 264 \text{ W}$

The panel's output falls to about 264 W in this example, from heat alone.

Problem 5 [Standard] A family in Duhok wants their example hybrid system to produce about 10 kWh per day. Using Duhok's example annual-average peak sun hours of 5.0 h/day (midpoint of the illustrative 4.8–5.2 range) and an example performance ratio of 0.80, what array size do they need, in kWp?

Solution

1. Rearrange the array-output equation: $P_{\text{array}} = E_{\text{array}} \div (\text{PSH} \times \text{PR})$
2. Put in the numbers: $P_{\text{array}} = 10 \text{ kWh} \div (5.0 \text{ h} \times 0.80)$

3. Calculate: $P_{\text{array}} = 10 \div 4.0 = 2.5 \text{ kWp}$

They need about a 2.5 kWp array, using this chapter's example numbers for Duhok.

Problem 6 [Standard] A remote clinic needs 6 kWh per day of backup energy and wants 2 days of autonomy (no sun and no generator). Using an example lithium battery depth of discharge (DoD) of 90% — the fraction of the battery's energy that can safely be used — and a system voltage of 48 V, find (a) the required battery energy capacity, in kWh, and (b) the required capacity, in Ah.

Solution

1. Energy needed over the autonomy period: $6 \text{ kWh/day} \times 2 \text{ days} = 12 \text{ kWh}$
2. Apply the depth of discharge: Battery capacity = $12 \text{ kWh} \div 0.90 \approx 13.3 \text{ kWh}$
3. Convert to Wh: $13.3 \text{ kWh} \times 1000 = 13,333 \text{ Wh}$
4. Convert to Ah: $13,333 \text{ Wh} \div 48 \text{ V} \approx 278 \text{ Ah}$

The clinic needs a battery bank of about 13.3 kWh, which is about 278 Ah at 48 V.

Problem 7 [Standard] Using this chapter's example generator energy cost recalled from Chapter 1 (about 380 IQD per kWh) and an example solar system that produces 12.7 kWh per day, how much money does a family save, in IQD per month (30 days), by using that solar energy instead of generator energy?

Solution

1. Monthly energy: $12.7 \text{ kWh/day} \times 30 = 381 \text{ kWh}$
2. Monthly savings: $381 \text{ kWh} \times 380 \text{ IQD/kWh}$
3. Calculate: 144,780 IQD

The family saves about 144,780 IQD per month in this example, by replacing generator energy with solar energy.

Problem 8 [Standard] An example off-grid system for a small shop costs 3,200,000 IQD in total. It saves the shop owner an example 90,000 IQD per month by reducing generator use. What is the simple payback period, in years?

Solution

1. Annual savings: $90,000 \text{ IQD/month} \times 12 = 1,080,000 \text{ IQD/year}$
2. Write the equation: $T_{\text{payback}} = C_{\text{system}} \div S_{\text{annual}}$
3. Put in the numbers: $T_{\text{payback}} = 3,200,000 \div 1,080,000 \approx 2.96 \text{ years}$

The simple payback period is about 2.96 years in this example — roughly 3 years.

Problem 9 [Standard] A school's example solar system produces 8,000 kWh per year. Using an example emission factor of 0.7 kg CO₂ per kWh, how much CO₂ does the school avoid per year, in kg and in tonnes?

Solution

1. Write the equation: $M_{\text{CO}_2} = E_{\text{annual}} \times EF$
2. Put in the numbers: $M_{\text{CO}_2} = 8,000 \text{ kWh} \times 0.7 \text{ kg/kWh}$
3. Calculate: $M_{\text{CO}_2} = 5,600 \text{ kg}$

4. Convert to tonnes: $5,600 \div 1000 = 5.6$ tonnes

The school avoids about 5,600 kg, or 5.6 tonnes, of CO₂ per year in this example.

Problem 10 [Standard] An array would produce 20 kWh per day with no losses. Using example estimates for practice — dust reduces output by 8%, and summer heat reduces the remaining output by another 10% — apply the two losses one after another to find the actual daily output.

Solution

1. Apply the dust loss: $20 \text{ kWh} \times (1 - 0.08) = 20 \times 0.92 = 18.4 \text{ kWh}$
2. Apply the heat loss to what remains: $18.4 \text{ kWh} \times (1 - 0.10) = 18.4 \times 0.90$
3. Calculate: 16.56 kWh

The actual output is about 16.56 kWh/day. Notice that two 'small' losses combine to a bigger total loss than simply adding 8% + 10%.

Problem 11 [Challenge] A farmer needs to lift 40 m^3 of water per day through a total head of 25 m for irrigation. (a) Using the standard water-lifting relation, Hydraulic energy (Wh) = $2.725 \times \text{Head (m)} \times \text{Volume (m}^3\text{)}$, find the ideal hydraulic energy needed per day. (b) If the pump and motor together are 45% efficient, find the actual electrical energy the solar pump system must supply per day. (c) Using an example peak sun hours value of 6.0 h/day for the pumping season, and assuming the array's full rated output is used while the sun shines (performance ratio = 1, for this simple pump example), what array size is needed, in kW?

Solution

1. (a) Hydraulic energy = $2.725 \times 25 \text{ m} \times 40 \text{ m}^3 = 2.725 \times 1,000 = 2,725 \text{ Wh} = 2.725 \text{ kWh}$
2. (b) Actual electrical energy = hydraulic energy $\div$ efficiency = $2.725 \text{ kWh} \div 0.45 \approx 6.06 \text{ kWh}$
3. (c) Array size = electrical energy $\div$ PSH = $6.06 \text{ kWh} \div 6.0 \text{ h} \approx 1.01 \text{ kW}$

The farm needs about 2,725 Wh of ideal hydraulic energy per day, which becomes about 6.06 kWh of real electrical energy once pump and motor losses are included, needing an array of roughly 1.0 kW in this example.

Problem 12 [Challenge] A design needs an array that produces at least 15 kWh per day on average, using an example performance ratio of 0.78. Using this chapter's example annual-average peak-sun-hour midpoints — Basra ≈ 5.35 h/day (from the 5.1–5.6 range) and Sulaymaniyah ≈ 5.0 h/day (from the 4.8–5.2 range) — find the required array size for each city, and state how much bigger, in percent, the Sulaymaniyah array must be compared with the Basra array to produce the same energy.

Solution

1. Basra array: $P = 15 \div (5.35 \times 0.78) = 15 \div 4.173 \approx 3.59 \text{ kWp}$
2. Sulaymaniyah array: $P = 15 \div (5.0 \times 0.78) = 15 \div 3.9 \approx 3.85 \text{ kWp}$
3. Difference: $3.85 - 3.59 = 0.26 \text{ kWp}$
4. Percent bigger: $0.26 \div 3.59 \times 100\% \approx 7.0\%$

In this example, Basra needs about 3.59 kWp and Sulaymaniyah needs about 3.85 kWp — Sulaymaniyah's array is about 7.0% bigger, because its example peak sun hours are a little lower.

Problem 13 [Challenge] A small health center needs reliable power. Its daily load is: lighting (8 LED lamps, 12 W each, 10 hours), a vaccine refrigerator (100 W, effectively running 12 hours), and small medical equipment and fans (250 W average, 8 hours). (a) Find the daily energy demand, in kWh. (b) Using an example peak sun hours value of 5.2 h/day and performance ratio 0.75, find the required array size, in kWp. (c) The clinic wants 1.5 days of battery autonomy at 90% depth of discharge, at a system voltage of 48 V. Find the required battery capacity, in kWh and in Ah. (d) If the whole system (array, battery, and the rest) costs an example 9,000,000 IQD, and saves the clinic an example 500,000 IQD per month versus its old generator-only setup, what is the simple payback period, in years?

Solution

1. (a) Lighting: $8 \times 12 \text{ W} \times 10 \text{ h} = 960 \text{ Wh}$. Refrigerator: $100 \text{ W} \times 12 \text{ h} = 1,200 \text{ Wh}$. Equipment/fans: $250 \text{ W} \times 8 \text{ h} = 2,000 \text{ Wh}$. Total = $960 + 1,200 + 2,000 = 4,160 \text{ Wh} = 4.16 \text{ kWh/day}$
2. (b) Array size: $P = 4.16 \text{ kWh} \div (5.2 \text{ h} \times 0.75) = 4.16 \div 3.9 \approx 1.07 \text{ kWp}$
3. (c) Stored energy needed: $4.16 \text{ kWh} \times 1.5 \text{ days} \div 0.90 \approx 6.93 \text{ kWh} = 6,933 \text{ Wh}$; in Ah: $6,933 \text{ Wh} \div 48 \text{ V} \approx 144 \text{ Ah}$
4. (d) Annual savings: $500,000 \text{ IQD/month} \times 12 = 6,000,000 \text{ IQD/year}$. Payback: $9,000,000 \div 6,000,000 = 1.5 \text{ years}$

This example clinic needs about 4.16 kWh/day, a 1.07 kWp array, a battery bank of about 6.93 kWh (about 144 Ah at 48 V), and would pay back its 9,000,000 IQD cost in about 1.5 years.

Problem 14 [Challenge] An example hybrid system costs 5,580,000 IQD and saves its owner about 1,737,000 IQD per year by reducing generator use. The system has a design life of 20 years. Ignoring maintenance costs and battery replacement (a simplification for this practice problem), what are the total lifetime savings over 20 years, and how many times bigger is that than the original system cost?

Solution

1. Total lifetime savings: $1,737,000 \text{ IQD/year} \times 20 \text{ years} = 34,740,000 \text{ IQD}$
2. Compare with system cost: $34,740,000 \div 5,580,000 \approx 6.2$

Over its full 20-year example life, this system's total savings are about 34,740,000 IQD — roughly 6.2 times what it cost, once it is already paid back. Real systems also need some maintenance cost and, for most battery types, at least one battery replacement before 20 years.

CHAPTER TWENTY-TWO

Capstone Design Projects

Self-Test — Questions and Answers

The Student Edition does not include this self-test. Give it in class, as homework, or as revision — every question includes its correct answer and a short explanation.

Q1. Which system type usually fits a remote telecommunications relay tower with no grid access at all?

- A. An off-grid system
- B. A plain grid-tied system
- C. A system with no panels or batteries, just a generator

Answer: An off-grid system. *A site with no grid connection at all must produce and store all its own energy, usually with a battery bank — this is exactly what an off-grid system does (Chapter 11; Project 9).*

Q2. A school building operates mainly during daylight hours and has a reliable grid connection. Which array-sizing approach normally fits it best?

- A. Off-grid sizing: the design-month peak sun hours, with full autonomy
- B. Grid-tied sizing: the annual average peak sun hours, with a consumption offset target
- C. No sizing calculation is needed, because schools use very little electricity

Answer: Grid-tied sizing: the annual average peak sun hours, with a consumption offset target. *Because the grid always covers any shortfall, a grid-tied array is normally sized to a chosen offset of the ANNUAL AVERAGE peak sun hours (Chapter 13; Project 2), not the worst month.*

Q3. A solar streetlight normally needs an inverter, because LED lights only run on AC power.

Answer: False. *Most solar streetlight fixtures are DC LED units, wired directly to the charge controller's load output — no inverter is needed at all (Project 7), the same DC-vs-AC choice Chapter 14 makes for pumps.*

Q4. A streetlight uses 25 W and operates for 12 hours each night, controlled by a dusk-to-dawn sensor. How much energy does it use per night, in Wh?

Answer: 300 Wh (± 5). $E = P \times t = 25 \text{ W} \times 12 \text{ h} = 300 \text{ Wh}$.

Q5. Which TWO of these sites should normally use a HIGH days-of-autonomy value (3–5 days or more), because losing power there is dangerous or very costly?

- A. A health center
- B. A telecommunications relay tower
- C. A family house that also keeps a generator for backup
- D. A shop that closes soon after sunset

Answer: A health center; A telecommunications relay tower. *Chapter 12, Lesson 3 places critical sites — health centers and telecom relays — at 3–5+ days of autonomy, because a power failure there is dangerous or very costly (Projects 6 and 9). A house with another backup, or a shop that closes early, can safely use a smaller autonomy or backup-hours value instead.*

Q6. A greenhouse's exhaust fans run mostly on hot, sunny summer afternoons, so its ENERGY use is much higher in summer than in winter. Why might its array still need to be sized using WINTER peak sun hours?

- A. Because winter's smaller baseline load, checked against much weaker winter sun, can sometimes need a bigger array than summer's larger load needs against strong summer sun
- B. Because winter never matters for a greenhouse and can always be ignored
- C. Because summer sun hours are always the deciding case for every seasonal load

Answer: Because winter's smaller baseline load, checked against much weaker winter sun, can sometimes need a bigger array than summer's larger load needs against strong summer sun. *Project 3 showed exactly this: winter's smaller baseline load (2900 Wh) needed about 1208 W of array, while summer's much bigger load (5660 Wh) needed only about 943 W, because summer's sun was more than twice as strong. Always check every season a load actually exists, not just its biggest-energy season.*

Q7. A borehole pump needs 900 Wh of hydraulic energy per day. The pump-and-motor combination is 45% efficient. How much electrical energy must it draw per day, in Wh?

Answer: 2000 Wh (± 20). $E_{elec} = E_{hyd} \div \eta_{pump} = 900 \div 0.45 = 2000 \text{ Wh}$. The pump must draw much more electrical energy than the useful hydraulic energy it delivers to the water.

Q8. Why do many hybrid family systems in this region use a SMALLER array than a fully off-grid design, for the exact same house?

- A. Because a hybrid array only needs to cover a chosen offset of average annual use, since the grid fills the rest of the need
- B. Because hybrid systems do not need any solar panels at all
- C. Because off-grid systems always use less daily energy than hybrid systems

Answer: Because a hybrid array only needs to cover a chosen offset of average annual use, since the grid fills the rest of the need. *Project 1 showed this directly: the same 4.0 kWh/day family needed a 2000 W off-grid array (full autonomy, design-month sun hours), but only an 800 W hybrid array (80% offset, annual average sun hours) once a grid connection existed to share the load.*

Q9. In a shared village mini-grid, the TOTAL daily energy needed by 20 homes is smaller than the sum of what 20 separate individual home systems would need, because of the demand factor.

Answer: False. Total daily ENERGY stays the same either way — 20 homes still use 20 homes' worth of lamps, fans, and chargers (Project 8). The demand factor can reduce the PEAK POWER a shared inverter must supply, because not every home uses everything at the same instant — but it does not reduce total energy.

Q10. A telecom equipment shelter already runs on 48 V DC power. What is the key safety concern when connecting new solar equipment to this existing plant?

- A. Telecom DC plants are often positive-grounded, the opposite of the usual solar convention, so polarity must be carefully checked before connecting anything
- B. Telecom equipment can never be powered by solar energy under any circumstances
- C. 48 V DC is always perfectly safe, so no special precautions are needed

Answer: Telecom DC plants are often positive-grounded, the opposite of the usual solar convention, so polarity must be carefully checked before connecting anything. *By industry convention, many telecom DC plants ground the POSITIVE terminal, not the negative terminal most solar equipment assumes by default (Project 9). Always confirm the site's grounding convention before connecting anything new.*

Q11. Which TWO of these are good reasons to add redundancy — for example, two smaller charge controllers instead of one big one — at a critical site like a health center?

- A. If one controller fails, the other can keep some charging happening
- B. Redundancy always makes the total system cheaper to buy
- C. It reduces the risk of losing ALL charging capacity to a single failure
- D. It completely removes the need for a backup generator

Answer: If one controller fails, the other can keep some charging happening; It reduces the risk of losing ALL charging capacity to a single failure. *Redundancy is about reliability, not lower cost — two smaller controllers usually cost more than one big one, and a backup generator can still be valuable alongside a*

redundant design. Its real benefit is that a single failed part cannot take down the whole system's charging capacity (Project 6).

Q12. A shop's array is sized for an 80% consumption offset. Its daily use is 3000 Wh, the annual average peak sun hours are 5.0 h/day, and the performance ratio is 0.80. Find the minimum array size, in watts.

Answer: 600 W (± 20). $P_{array} = (Offset \times E_{daily}) \div (PSH_{avg} \times PR) = (0.8 \times 3000) \div (5.0 \times 0.8) = 2400 \div 4.0 = 600 \text{ W}.$

Practice Problems — Full Solutions

Every problem is repeated here with its complete, step-by-step solution.

Problem 1 [Basic] A streetlight uses 25 W and runs for 12 hours each night, controlled by a dusk-to-dawn sensor. How much energy does it use in one night, in Wh?

Solution

1. Write the equation: $E = P \times t$
2. Put in the numbers: $E = 25 \text{ W} \times 12 \text{ h}$
3. Calculate: $E = 300 \text{ Wh}$

The streetlight uses 300 Wh of energy each night.

Problem 2 [Basic] A telecom relay's radio equipment draws a steady 120 W and runs 24 hours a day, every day. Find its daily energy use, in Wh and kWh.

Solution

1. Write the equation: $E = P \times t$
2. Put in the numbers: $E = 120 \text{ W} \times 24 \text{ h} = 2880 \text{ Wh}$
3. Convert to kWh: $2880 \div 1000 = 2.88 \text{ kWh}$

The equipment uses 2880 Wh, or 2.88 kWh, every single day — this never changes, because it runs continuously.

Problem 3 [Basic] A shop's drinks refrigerator is rated 140 W. Its compressor effectively runs about 9 hours a day. Find its daily energy use, in Wh.

Solution

1. Write the equation: $E = P \times t$
2. Put in the numbers: $E = 140 \text{ W} \times 9 \text{ h}$
3. Calculate: $E = 1260 \text{ Wh}$

The refrigerator uses about 1260 Wh (1.26 kWh) per day.

Problem 4 [Basic] A solar pump's datasheet gives its flow rate as 50 liters per minute (L/min). Convert this to cubic meters per second (m^3/s), the unit needed for the hydraulic power equation.

Solution

1. Convert L/min to L/s: $50 \div 60 \approx 0.833 \text{ L/s}$
2. Convert L/s to m^3/s : $0.833 \div 1000 \approx 0.000833 \text{ m}^3/\text{s}$

3. Check with the one-step shortcut: $50 \div 60,000 \approx 0.000833 \text{ m}^3/\text{s}$

The flow rate is about $0.000833 \text{ m}^3/\text{s}$.

Problem 5 [Basic] A family's washing machine uses 500 W and runs for 45 minutes each day. Find its daily energy use, in Wh. (Careful: convert minutes to hours first.)

Solution

1. Convert time: 45 minutes = $45 \div 60 = 0.75 \text{ h}$
2. Write the equation: $E = P \times t$
3. Put in the numbers: $E = 500 \text{ W} \times 0.75 \text{ h} = 375 \text{ Wh}$

The washing machine uses 375 Wh on a day it runs.

Problem 6 [Standard] A solar streetlight needs 275 Wh of energy each night. The design uses 2 days of autonomy, a 12 V system, and LiFePO4 batteries with a maximum depth of discharge of 0.8. Find the required battery bank capacity, in Ah.

Solution

1. Write the equation: $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (275 \times 2) \div (12 \times 0.8)$
3. Calculate the top: $275 \times 2 = 550 \text{ Wh}$
4. Calculate the bottom: $12 \times 0.8 = 9.6$
5. Divide: $C_{\text{bank}} = 550 \div 9.6 \approx 57.3 \text{ Ah}$

The battery bank needs at least about 57.3 Ah at 12 V.

Problem 7 [Standard] A rural clinic wants a small emergency lighting circuit, totaling 250 W, to keep working for 3 hours during any power interruption. Using a 24 V system and lithium batteries with DoD = 0.8, find the required battery capacity, in Ah.

Solution

1. Write the equation: $C_{\text{bank}} = (P_{\text{critical}} \times t_{\text{backup}}) \div (V_{\text{sys}} \times \text{DoD})$
2. Put in the numbers: $C_{\text{bank}} = (250 \times 3) \div (24 \times 0.8)$
3. Calculate the top: $250 \times 3 = 750 \text{ Wh}$
4. Calculate the bottom: $24 \times 0.8 = 19.2$
5. Divide: $C_{\text{bank}} = 750 \div 19.2 \approx 39.1 \text{ Ah}$

The emergency lighting circuit needs at least about 39.1 Ah at 24 V.

Problem 8 [Standard] A small telecom array has a short-circuit current (I_{sc}) of 21 A. Using the 1.25 safety factor, find the minimum charge controller current rating, then round up to the nearest standard size (10, 20, 30, 40, 50, 60, 80, 100 A).

Solution

1. Write the check: $I_{\text{controller}} \geq I_{\text{sc}} \times 1.25$
2. Put in the numbers: $I_{\text{controller}} \geq 21 \times 1.25 = 26.25 \text{ A}$

3. Round up to the nearest standard size: 30 A

Choose at least a 30 A charge controller.

Problem 9 [Standard] A greenhouse's exhaust fan uses 250 W and runs for 5 hours on a summer afternoon. (a) Find its energy use for that day, in Wh. (b) Using summer peak sun hours of 7.2 h/day and a performance ratio of 0.80, find the minimum array power needed to cover this fan alone.

Solution

1. Part (a): $E = P \times t = 250 \text{ W} \times 5 \text{ h} = 1250 \text{ Wh}$
2. Part (b): write the array equation: $P_{\text{array}} = E_{\text{daily}} \div (\text{PSH} \times \text{PR})$
3. Put in the numbers: $P_{\text{array}} = 1250 \div (7.2 \times 0.80) = 1250 \div 5.76$
4. Calculate: $P_{\text{array}} \approx 217.0 \text{ W}$

(a) The fan uses 1250 Wh on that day. (b) Covering this fan alone would need an array of about 217 W.

Problem 10 [Standard] A pump delivers a flow rate of 40 L/min against a total dynamic head of 18 m. Find the hydraulic power, in W. (Convert the flow rate to m^3/s first, and use $\rho = 1000 \text{ kg}/\text{m}^3$, $g = 9.81 \text{ m}/\text{s}^2$.)

Solution

1. Convert flow rate: $Q = 40 \div 60,000 \approx 0.000667 \text{ m}^3/\text{s}$
2. Write the equation: $P_{\text{hyd}} = \rho \times g \times Q \times H$
3. Put in the numbers: $P_{\text{hyd}} = 1000 \times 9.81 \times 0.000667 \times 18$
4. Calculate: $P_{\text{hyd}} \approx 117.7 \text{ W}$

The hydraulic power is about 117.7 W.

Problem 11 [Standard] A shop wants its array to offset 70% of its average daily use of 2800 Wh. Using an annual average peak sun hours of 5.3 h/day and a performance ratio of 0.80, find the minimum array power, in W.

Solution

1. Write the equation: $P_{\text{array}} = (\text{Offset} \times E_{\text{daily}}) \div (\text{PSH}_{\text{avg}} \times \text{PR})$
2. Put in the numbers: $P_{\text{array}} = (0.70 \times 2800) \div (5.3 \times 0.80)$
3. Calculate the top: $0.70 \times 2800 = 1960 \text{ Wh}$
4. Calculate the bottom: $5.3 \times 0.80 = 4.24$
5. Divide: $P_{\text{array}} = 1960 \div 4.24 \approx 462.3 \text{ W}$

The minimum array size is about 462.3 W.

Problem 12 [Challenge] A remote cluster of 15 similar homes each need 850 Wh per day. A shared community pump house needs another 1200 Wh per day. (a) Find the total daily energy for the whole group. (b) Using a design-month peak sun hours of 3.2 h/day and a performance ratio of 0.78, find the minimum shared array size, in kWp.

Solution

1. (a) Homes: $15 \times 850 = 12,750 \text{ Wh}$
2. (a) Add the pump house: $12,750 + 1200 = 13,950 \text{ Wh}$

3. (b) Write the equation: $P_{\text{array}} = E_{\text{daily}} \div (\text{PSH} \times \text{PR})$
 4. (b) Put in the numbers: $P_{\text{array}} = 13,950 \div (3.2 \times 0.78) = 13,950 \div 2.496$
 5. (b) Calculate: $P_{\text{array}} \approx 5588.9 \text{ W} \approx 5.59 \text{ kWp}$
- (a) The group needs 13,950 Wh (13.95 kWh) per day. (b) The shared array needs at least about 5.59 kWp.**

Problem 13 [Challenge] A school uses an average of 18,000 Wh per day. It wants a 75% consumption offset, using an annual average peak sun hours of 5.1 h/day and a performance ratio of 0.80. (a) Find the minimum array power, in W. (b) Using 350 W panels, find how many panels are needed, rounded up, and the actual array power.

Solution

1. (a) Write the equation: $P_{\text{array}} = (\text{Offset} \times E_{\text{daily}}) \div (\text{PSH}_{\text{avg}} \times \text{PR})$
 2. (a) Put in the numbers: $P_{\text{array}} = (0.75 \times 18,000) \div (5.1 \times 0.80) = 13,500 \div 4.08$
 3. (a) Calculate: $P_{\text{array}} \approx 3308.8 \text{ W}$
 4. (b) Divide by the panel size: $3308.8 \div 350 \approx 9.45$
 5. (b) Round up to a whole number of panels: 10 panels = 3500 W
- (a) The minimum array size is about 3308.8 W (3.31 kWp). (b) Ten 350 W panels (3500 W total) are needed.**

Problem 14 [Challenge] A telecom site's daily electrical need, including its design margin, is 3800 Wh. The design uses 4 days of autonomy, a 48 V system, and LiFePO₄ batteries with DoD = 0.8. (a) Find the required battery bank capacity, in Ah. (b) Using 12 V, 150 Ah batteries wired 4 in series (for 48 V), find how many parallel strings are needed, and the actual battery bank capacity.

Solution

1. (a) Write the equation: $C_{\text{bank}} = (E_{\text{daily}} \times N_{\text{auto}}) \div (V_{\text{sys}} \times \text{DoD})$
 2. (a) Put in the numbers: $C_{\text{bank}} = (3800 \times 4) \div (48 \times 0.8) = 15,200 \div 38.4$
 3. (a) Calculate: $C_{\text{bank}} \approx 395.8 \text{ Ah}$
 4. (b) Strings needed: $395.8 \div 150 \approx 2.64 \rightarrow$ round up to 3 parallel strings
 5. (b) Total batteries: 4 in series $\times$ 3 strings = 12 batteries, giving an actual $4 \times 12 \text{ V} = 48 \text{ V}$, $3 \times 150 = 450 \text{ Ah}$
- (a) The battery bank needs at least about 395.8 Ah at 48 V. (b) Three parallel strings of 4 series batteries (12 batteries total) give an actual 450 Ah — comfortably above the requirement.**