17 *Sustainability Economics: Carbon, Life-Cycle Cost, and the Circular Economy*

After this chapter you will be able to:

1. compute the annual carbon cost of a project from its emission factor and a carbon price in SAR per tonne of CO_2e
2. distinguish a regulated carbon price, which is a real cash flow, from an internal shadow price, which changes only the ranking
3. compute the flip price p^* at which two alternatives tie, and present it as a one-way carbon-price sweep
4. compute the life-cycle cost $\text{LCC} = P_{\text{acq}} + PW_{\text{opr}} + PW_{\text{mnt}} + PW_{\text{eol}}$ of a purchase
5. choose one of three treatments for an externality: regulated price, shadow price, or unpriced disclosure
6. explain how a higher end-of-life value S_N from recovery or recycling can move the economic service life

Every criterion in this book so far has priced cash flows that appear on an invoice: purchases, fuel bills, salvage cheques. This chapter extends the same machinery to costs that do not, or do not yet, appear on any invoice. Three extensions are developed, and none of them requires a new formula. First, a firm can attach a money value to each tonne of carbon dioxide its projects emit and carry that value through present worth and annual equivalence like any other cost line; the levelized-cost comparison of diesel against solar power from section 6.7 returns here, and a carbon price is exactly the kind of input that can flip its verdict. Second, *life-cycle cost analysis* disciplines a purchase decision to count everything from acquisition to disposal, discounted, so that a pump that is cheap to buy but expensive to run and expensive to retire can be seen for what it is. Third, the *circular economy* changes the last cash flow of an asset's life: when a retired machine is a source of parts and materials rather than a disposal problem, its end-of-life value rises, and decisions made in chapter 16, such as the economic service life, can move. Throughout, the discounting is the discounting of chapter 2; what changes is only which flows are allowed onto the diagram.

What a price tag leaves out.

Q1. A firm adopts an internal carbon price of 100 SAR per tonne of CO_2e for project evaluation, in a country with no carbon tax. When a project emits a tonne, does the firm pay 100 SAR to anyone?

Q2. Pump A costs 40,000 SAR to buy and Pump B costs 95,000 SAR. Is Pump A the cheaper pump?

Q3. A recycler pays 6,000 SAR for a machine that would otherwise cost 2,000 SAR to dispose of. On the cash flow diagram at the end of the asset's life, what changes?

Answers.

Q1. *No.* An internal carbon price in an unregulated jurisdiction is a *shadow* price: it enters the project comparison as if it were a cost, so that lower-carbon alternatives rank better, but no cash leaves the firm. Only a regulated price (a carbon tax or a permit price) creates an actual cash flow.

Q2. *Unknown.* The question compares acquisition costs only. The life-cycle cost adds operating, maintenance, and end-of-life flows, discounted; a pump that is cheap to buy is often expensive to own. The worked example in this chapter makes Pump A lose by a wide margin.

Q3. The year-N arrow flips: a 2,000 SAR downward arrow (a disposal cost) becomes a 6,000 SAR upward arrow (a recovery revenue), a swing of 8,000 SAR at year N. It is discounted like any salvage value.

Reference. World Bank, *Carbon Pricing Dashboard* and *State and Trends of Carbon Pricing 2025*; CDP (2021). Full references at the end of the chapter.

Tonne of CO_2e. One metric tonne of carbon dioxide equivalent (tCO_2e): the common unit for greenhouse-gas emissions, with other gases converted to the amount of CO_2 with the same warming effect.

Carbon price. A money value per tonne of CO_2e emitted. It can be *regulated* (a tax or permit price that must actually be paid) or *internal* (a value the firm chooses to apply to its own decisions).

17.1 *Putting a Price on Carbon*

Carbon pricing is no longer exotic. The World Bank's Carbon Pricing Dashboard counts 113 direct carbon pricing instruments implemented across 55 national and 44 subnational jurisdictions, of which 37 are emissions trading systems and 43 are carbon taxes. Its *State and Trends of Carbon Pricing 2025* report puts about 28% of global greenhouse-gas emissions under a carbon price, up from 12% a decade earlier, and reports that these instruments raised more than 100 billion USD for public budgets in 2024. A firm in a jurisdiction with a carbon tax simply has a new operating cost, and nothing in this book needs to change: the tax is a cash flow like a fuel bill.

Internal (shadow) carbon price. A carbon price the firm applies in its own project evaluations even where no regulation requires payment. It changes rankings, not bank balances.

The more interesting case is the firm that faces no carbon regulation today but prices carbon anyway. CDP, which runs the world's largest corporate environmental disclosure system, reported that of nearly 6,000 companies surveyed in 2020, more than 2,000 already used an internal carbon price or planned to adopt one within two years, an 80% increase over five years, and that the median disclosed price was 25 USD per tCO_2e, which is about 94 SAR at 3.75 SAR per USD. Firms do this to prepare for regulation that may arrive during a project's life, to steer capital toward lower-carbon designs before it is forced, and to answer investors who ask the question directly.

The mechanics are the plainest part. Estimate the project's emissions in tonnes of CO_2e per year, multiply by the carbon price to get a cost in SAR per year, and let that line join the other operating costs in the present worth or annual equivalent. Everything downstream, discounting, ranking, break-even, is unchanged.

Insight. What a shadow price does and does not do. An internal carbon price in an unregulated jurisdiction changes no cash flow: the firm's bank account is identical with or without it. What it changes is the *ranking* of alternatives, because high-emission options are charged inside the comparison and low-emission options are not. A shadow price is therefore a policy statement expressed in the only language a project comparison understands, SAR per year. The discipline it imposes is consistency: the same price must be applied to every alternative and every project, or the ranking it produces means nothing.

In practice. The tonnes are engineering data before they are money. A diesel genset burns about 0.28 liters of fuel per kilowatt-hour delivered, and each liter of diesel releases about 2.68 kg of CO_2e, so the emission factor is $0.28 \times 2.68 \approx 0.75$ kg of CO_2e per kWh. Metered fuel consumption, not a brochure figure, should set this number, exactly as measured loads set energy costs in chapter 6.

Example 17.1 — A carbon cost line for the mine's gensets

The remote mine of Example 6.7 generates 20 GWh (20,000,000 kWh) per year from diesel gensets with an emission factor of 0.75 kg of CO_2e per kWh. The firm adopts an internal carbon price of 100 SAR per tCO_2e. Express the carbon cost as an annual cost line, and find its present worth over the gensets' remaining 10-year life at the mine's MARR of 8%.

Solution.

Step 1: tonnes per year.

$$20{,}000{,}000 \times \frac{0.75}{1{,}000} = 15{,}000 \text{ tCO}_2\text{e per year.}$$

Step 2: the cost line.

$$15{,}000 \times 100 = 1{,}500{,}000 \text{ SAR per year.}$$

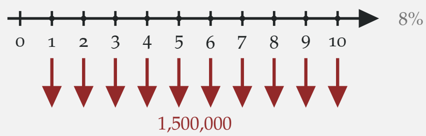

Figure 17.1. The internal carbon price as a uniform annual cost line over the gensets' remaining life. It discounts like any other operating cost.

Step 3: discount it.

With $(P/A, 8\%, 10) = 6.7101$:

$$PW_{\text{carbon}} = 1{,}500{,}000\,(6.7101) = \boxed{10{,}065{,}150 \text{ SAR}}.$$

At the firm's own chosen price, the gensets' emissions are a 10-million-SAR liability in present-worth terms. No invoice exists for this amount, and none may ever exist; the number's job is to make every comparison involving the gensets carry the emissions on the ledger, so that a cleaner alternative competes against the true, policy-weighted cost of diesel.

17.2 *When the Carbon Price Flips a Decision*

A cost line matters only if it can change a verdict. Return to the mine power comparison of Example 6.7, which ended with a warning: at a 25% capacity factor, the solar-plus-storage plant cannot carry the mine alone, so the gensets stay for the hours the storage cannot cover, and the real decision is what fraction of the load to shift. The daytime block was easy, 0.284 SAR per kWh for solar against 0.977 SAR per kWh for diesel, and no carbon price is needed to decide it. The contested block is the night load.

Example 17.2 — The flip price for the night block

The developer offers to extend the mine's solar plant to cover a night-load block. Per kilowatt of night load: additional panels and batteries cost 7,700 SAR installed, fixed O&M is 50 SAR per year, the battery-limited life is 10 years, and after round-trip losses the block delivers 1,100 kWh per year. Diesel serves the same block at its LCOE of 0.977 SAR per kWh from Example 6.7, with an emission factor of 0.75 kg of CO_2e per kWh; the solar block's operating emissions are taken as zero. The MARR is 8%. (a) Find the night block's levelized cost and the verdict with no carbon price. (b) Find the internal carbon price at which the verdict flips.

Solution.

(*a*) *The night block's LCOE.*

With $(A/P, 8\%, 10) = 0.14903$:

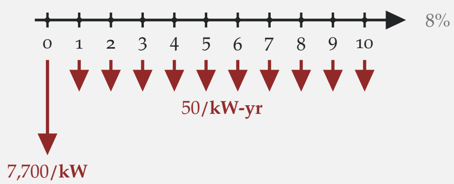

Figure 17.2. One kilowatt of the night block: panels plus batteries at year 0 and fixed O&M over the battery-limited 10-year life.

$$\text{LCOE}_{\text{night}} = \frac{7{,}700\,(0.14903) + 50}{1{,}100} = \frac{1{,}147.5 + 50}{1{,}100} = \boxed{1.089 \text{ SAR per kWh}}.$$

With no carbon price, diesel wins the night block: 0.977 against 1.089 SAR per kWh, a margin of about 0.112 SAR per kWh. The verdict is the reverse of the daytime one, and both are correct: the same technology pair, costed honestly block by block.

(*b*) *The flip price.*

A carbon price of p SAR per tCO_2e adds $0.75\,p/1{,}000$ SAR to each diesel kilowatt-hour and nothing to the solar one. The verdict flips where the two costs are equal:

$$0.977 + \frac{0.75\,p}{1{,}000} = 1.089 \quad\Longrightarrow\quad p^* = \frac{1.089 - 0.977}{0.00075} = \boxed{149 \text{ SAR per tCO}_2\text{e}}.$$

That is about 40 USD per tonne. Now the published prices give the number meaning. At CDP's median internal price of 25 USD (about 94 SAR), diesel still wins the night block, $0.977 + 0.070 = 1.047$ against 1.089. At a price near the upper range of implemented compliance prices, say 300 SAR (80 USD), diesel costs $0.977 + 0.225 = 1.202$ SAR per kWh and the solar extension wins clearly. The engineering did not change between those two sentences; the policy input did, and the flip price is the exact boundary between them.

Insight. The flip price is a break-even value in disguise. In chapter 12, break-even analysis asked: at what value of an uncertain input does the decision change? Here the uncertain input is the carbon price itself, whether a future regulated price or the firm's own evolving internal one. Computing p^* does not require anyone to know the right price of carbon; it converts the decision into a question a board can actually answer: do we believe carbon will cost more or less than 149 SAR per tonne over the life of this plant?

Reference. ISO 15686-5, *Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing*, defines the standard cost breakdown used here. See also Park, 3rd ed., Chapter 6, for the AE machinery.

Life-cycle cost (LCC). The present worth of all costs of owning an asset over its whole life: acquisition, operation, maintenance, and end-of-life, minus any end-of-life recovery.

17.3 *Life-Cycle Cost Analysis*

Purchasing decisions are often made on the price tag. Life-cycle cost analysis is the discipline that refuses this shortcut. The international standard ISO 15686-5 organizes an asset's costs into four groups, and the LCC is their discounted sum:

$$\mathrm{LCC}(i) = \underbrace{P_{\mathrm{acq}}}_{\text{acquisition}} + \underbrace{PW_{\mathrm{opr}}(i)}_{\text{operation}} + \underbrace{PW_{\mathrm{mnt}}(i)}_{\text{maintenance}} + \underbrace{PW_{\mathrm{eol}}(i)}_{\text{end-of-life}}, \tag{17.1}$$

where the end-of-life term is positive for a disposal cost and negative for a recovery revenue. Nothing in Equation (17.1) is new mathematics: it is the PW of cost from chapter 5, with a checklist attached. The checklist is the contribution. Acquisition is the visible term; operation and maintenance are where energy-hungry or failure-prone equipment loses; and end-of-life is the term analyses omit most often, because it is distant, uncertain, and belongs to whoever holds the asset last.

Example 17.3 — Two pumps, one honest comparison

A process plant needs a slurry transfer pump for 10 years of service; the MARR is 10%. Two offers are on the table.

- **Pump A (low bid):** price 40,000 SAR; energy and consumables 22,000 SAR per year; maintenance 7,000 SAR per year; a wet-end overhaul of 12,000 SAR at the end of year 5; at end of life it is contaminated scrap costing 4,000 SAR to dispose of.
- **Pump B (premium):** price 95,000 SAR; energy and consumables 14,000 SAR per year; maintenance 3,000 SAR per year; no mid-life overhaul; at end of life the manufacturer's take-back program pays 8,000 SAR for the unit.

Compute the life-cycle cost of each pump and state the decision.

Solution.

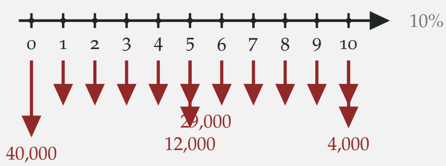

Figure 17.3. Pump A: a small price tag followed by heavy operating, an overhaul at year 5, and a disposal cost at year 10.

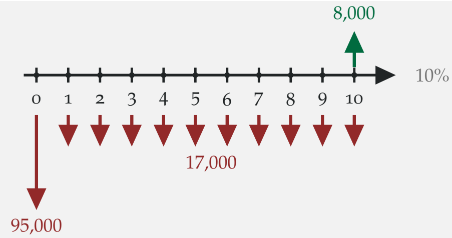

Figure 17.4. Pump B: a large price tag, light operating, and a take-back payment instead of a disposal cost.

Step 1: collect each pump's annual total.

Pump A runs at $22{,}000 + 7{,}000 = 29{,}000$ SAR per year; Pump B at $14{,}000 + 3{,}000 = 17{,}000$ SAR per year.

Step 2: discount everything.

With $(P/A, 10\%, 10) = 6.1446$, $(P/F, 10\%, 5) = 0.6209$, and $(P/F, 10\%, 10) = 0.3855$:

$$\begin{aligned}
\text{LCC}_A &= 40{,}000 + 29{,}000\,(6.1446) + 12{,}000\,(0.6209) + 4{,}000\,(0.3855) \\
&= 40{,}000 + 178{,}193 + 7{,}451 + 1{,}542 = \boxed{227{,}186 \text{ SAR}}, \\
\text{LCC}_B &= 95{,}000 + 17{,}000\,(6.1446) - 8{,}000\,(0.3855) \\
&= 95{,}000 + 104{,}458 - 3{,}084 = \boxed{196{,}374 \text{ SAR}}.
\end{aligned}$$

Step 3: decision sentence.

Buy Pump B: over ten years of service it is cheaper by about 30,800 SAR in present-worth terms, even though it costs more than twice as much to acquire. Note where the verdict was decided: Pump A's purchase price is only $40{,}000/227{,}186 \approx 18\%$ of its life-cycle cost. The price tag, the one number the low bid was selected on, is the smallest of the four groups in Equation (17.1).

Insight. Why end-of-life terms deserve attention even though discounting shrinks them. In Example 17.3, the year-10 flows moved the answer by less than 5,000 SAR against a 30,800 SAR margin, and it is tempting to conclude that end-of-life never matters. The conclusion is wrong twice. First, when the operating costs of two options are close, the end-of-life gap is the margin. Second, for some assets the end-of-life term is not small: decommissioning a tailings facility or dismantling an offshore structure can rival the original construction cost, and a discount rate does not make a nine-figure obligation disappear, it only prices its distance. The honest rule is the checklist rule: the term is always estimated, and only then, sometimes, found to be negligible.

Externality. A cost (or benefit) that a project imposes on parties outside the firm and that no market transaction prices: emissions, noise, dust, water drawdown, congestion.

17.4 *Externalities: Three Ways to Handle a Cost Nobody Bills*

Carbon is one member of a family. Dust from a haul road settles on a village; a wellfield draws down an aquifer shared with farms; a night shift's lighting and noise cross the fence line. These are *externalities*: real costs, borne by real people, billed to no one. An engineering economist has exactly three defensible ways to bring an externality into an analysis, and the discipline is to know which one is in use and say so.

Regime	What it is	Where it enters	Example
Regulated price	A law makes the firm pay per unit of the externality	A genuine cash flow in PW/AE, like any operating cost	A carbon tax; a volumetric water abstraction fee
Shadow price	The firm (or an appraisal standard) assigns a price with no payment obligation	A cost line in the *comparison* only; reported separately from cash	An internal carbon price of 100 SAR per tCO_2e
Unpriced disclosure	No defensible price exists; the quantity is measured and reported next to the money answer	Outside the PW entirely; in the decision document as its own column	''Option D: PW of cost 1.2M SAR, 40 t of dust per year''

Table 17.1. Three regimes for an externality. Moving an item up this table (from disclosure toward regulated price) is a policy act, not an engineering one.

Table 17.1 carries one warning worth a whole exam question. A shadow price and a regulated price produce identical arithmetic inside a comparison, but they are different claims about the world. A regulated price will appear in the firm's accounts; a shadow price never will. An analysis that quietly adds a shadow-priced ''saving'' to a project's cash inflows, and then reports the total as if it were money the firm will receive, has manufactured revenue out of a policy assumption. The end-of-chapter audit exercises return to exactly this error.

In practice. Exporters meet externality pricing at the border. Several large markets now charge imports for their embedded carbon, so a supplier into those markets can face a real, regulated carbon cost even though its home jurisdiction prices nothing. In the language of this section: someone else's regulation converts your shadow price into a cash flow.

Insight. Which regime applies is a fact to verify, not a preference. The World Bank dashboard cited in this chapter exists precisely so an analyst can check whether a jurisdiction prices carbon and at roughly what level. Treating a priced externality as unpriced understates costs; treating an unpriced one as cash overstates revenues. Both errors are common, and both are checkable in minutes.

Circular economy. An industrial pattern in which retired products and materials re-enter production, through reuse, remanufacture, or recycling, instead of leaving the economy as waste.

End-of-life value. The net cash flow when an asset leaves service: resale or recovery revenue minus removal and disposal costs. It can be positive or negative, and it discounts like a salvage value.

In practice. Design for disassembly sets the end-of-life price years in advance. A gearbox that unbolts in an hour is a remanufacturable core; one that is welded in is shredder feed. The designer's choices of fasteners, material labeling, and modularity decide which column of the recycler's price list the asset lands in, long before any economist discounts it.

17.5 *The Circular Economy at End of Life*

Every replacement decision in chapter 16 ended with a market value S_N: the truck is sold, the story ends. The circular economy widens the menu at that final node. A retired asset can be resold whole, harvested for remanufacturable cores such as drivetrains and gearboxes, granted a second life in a less demanding duty, or shredded for material recovery. Each channel has its own price, and the analysis simply takes the best one. In cash flow terms the effect is a single, familiar move: the end-of-life arrow grows, or flips from a disposal cost into a recovery revenue, and everything built on that arrow, the capital recovery cost of chapter 6, the economic service life of chapter 16, moves with it.

Example 17.4 — A recycler moves the economic service life

In Example 16.4, the challenger truck ($I = 72{,}000$ SAR, $i = 10\%$) had its economic service life at $N^* = 3$ years with $AEC^* = 30{,}094$ SAR per year; keeping it a fourth year cost 30,138 SAR per year, because the resale market for a 4-year-old truck is thin ($S_4 = 26{,}000$ SAR). A certified parts-recovery firm now offers a take-back price of 32,000 SAR for 4-year-old units, valuing the drivetrain core and recoverable materials individually. (At age 3 its offer is below the 33,000 SAR used-market value, so nothing changes there.) Recompute the $N = 4$ row and the economic service life.

Solution. Only the year-4 capital flows change; the operating-cost column of Example 16.4 is untouched.

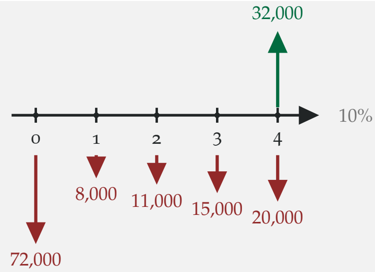

Figure 17.5. The ''keep 4 years'' policy with the recycler's take-back price replacing the thin used-market value at year 4.

Step 1: the new capital recovery cost at $N = 4$.

With $(A/P, 10\%, 4) = 0.31547$ and $S_4 = 32{,}000$ SAR:

$$CR = (72{,}000 - 32{,}000)(0.31547) + 0.10\,(32{,}000)$$
$$= 12{,}619 + 3{,}200 = 15{,}819 \text{ SAR per year.}$$

Step 2: the new total.

The operating annual equivalent for $N = 4$ was 13,027 SAR per year in Example 16.4:

$$AEC(4) = 15{,}819 + 13{,}027 = \boxed{28{,}846 \text{ SAR per year}}.$$

Step 3: re-read the table.

The four rows are now 33,200, 30,914, 30,094, and 28,846 SAR per year. The minimum has moved:

$$\boxed{N^* = 4 \text{ years, with } AEC^* = 28{,}846 \text{ SAR per year}},$$

about 1,248 SAR per year cheaper than the old optimum. One recovery channel at one age changed a fleet-policy answer: the trucks should now be kept a year longer, and every replacement comparison in chapter 16 that used 30,094 SAR per year as the challenger's benchmark should be redone with 28,846.

Insight. A recovery premium does not always lengthen lives. Suppose the recycler paid a flat 3,000 SAR premium over market value at *every* age. The premium reduces $AEC(N)$ by 3,000 $[(A/P, i, N) - i]$, which is 3,000 $\times$ 1.00 at $N = 1$ but only 3,000 $\times$ 0.2155 at $N = 4$: the shorter the keep-period, the more often the premium is collected, so a uniform premium favors *shorter* lives. In Example 17.4, the life lengthened only because the premium was specific to age 4. The direction of the shift is a computation, not an intuition.

Closing the loop: a remark on lithium

The clearest industrial picture of these ideas is the battery-metals loop: ore is mined, refined into battery-grade chemicals, built into cells, and, a decade later, the retired cells are collected, their metals recovered, and the recovered material re-enters the refining step, displacing a portion of new ore. Every link of that loop is an engineering-economy problem from this book: the mine and the refinery are screened as investments under chapter 5; the cell plant prices its output as a minimum sustainable price under chapter 6; the retired cells have an end-of-life value that improves with design for disassembly; and the recycler's viability is a unit-cost calculation whose feedstock price is someone else's negative disposal cost. When the recovered material is cheaper than freshly mined material at the refinery gate, the loop closes by economics rather than by mandate. None of this requires new criteria; it requires the old criteria applied at every node, including the last one.

17.6 Carbon-Price Sensitivity: A One-Way Analysis

Nobody knows what carbon will cost over a 25-year project life, which is precisely why the tools of chapter 12 apply. A carbon price is an uncertain input like any other, and the honest presentation is a one-way sensitivity analysis (section 12.3): hold everything else at its base case, sweep the carbon price, and show where the verdict changes.

Example 17.5 — One-way sweep of the carbon price

For the night block of Example 17.2, express each option's levelized cost as a function of the carbon price p (SAR per tCO_2e), plot both, and read off the decision regions.

Solution. The solar block is flat in p; diesel climbs at its emission factor:

$$\text{LCOE}_{\text{night}}(p) = 1.089, \qquad \text{LCOE}_{\text{diesel}}(p) = 0.977 + 0.00075\,p.$$

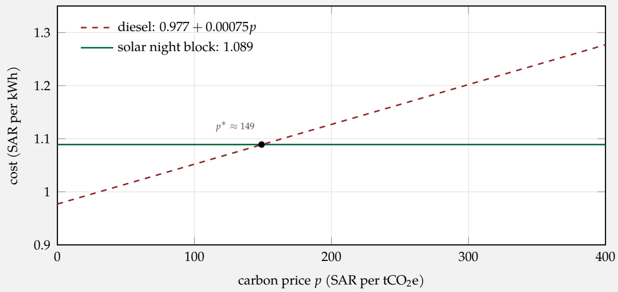

Figure 17.6. One-way sensitivity of the night-block decision to the carbon price. The lines cross at the flip price; below it diesel is cheaper, above it the solar extension is.

The picture says everything the board needs: diesel wins for $p < 149$ SAR per tCO_2e, solar wins above, and the base-case margin at $p = 0$ is small enough (0.112 SAR per kWh) that the carbon assumption, not the engineering estimates, is the decisive input. Compare the slope structure with Example 6.7: solar's cost lives in the discount rate, diesel's lives in fuel and now in carbon. Each technology is exposed to a different uncertainty, and a one-way sweep per input is the compact way to show which exposure bites.

17.7 *Case Study from the Literature*

Internal carbon prices are not textbook inventions; they are disclosed, counted, and published. Two public sources anchor this chapter's numbers. The World Bank's Carbon Pricing Dashboard, the public companion to its annual *State and Trends of Carbon Pricing* report, tracks every implemented compliance instrument in the world: at the time of writing it lists 113 implemented instruments (37 emissions trading systems, 43 carbon taxes, and 33 governmental crediting mechanisms) across 55 national and 44 subnational jurisdictions. The 2025 report behind it states that about 28% of global greenhouse-gas emissions now carry a carbon price, that coverage has grown from 12% a decade earlier, and that carbon pricing raised over 100 billion USD for public budgets in 2024. On the corporate side, CDP's disclosure data (2021) reported more than 2,000 of nearly 6,000 surveyed companies using or planning an internal carbon price, with a median disclosed price of 25 USD per tCO_2e. The case study below takes that median corporate price and runs it through this book's machinery for the mine of Example 6.7.

Reference. World Bank, *Carbon Pricing Dashboard* (accessed July 2026) and *State and Trends of Carbon Pricing 2025*; CDP (2021). Full references at the end of the chapter.

Example 17.6 — Case study: the median disclosed price, applied

Apply CDP's median disclosed internal carbon price, 25 USD per tCO_2e, to the mine's genset fleet of Example 17.1: 20 GWh per year at 0.75 kg of CO_2e per kWh. Use 3.75 SAR per USD, a 15-year horizon, and the mine's 8% MARR. Find the annual carbon cost line, its present worth, and its effect on the diesel LCOE.

Solution.

Step 1: the price in SAR.

$$25 \times 3.75 = 93.75 \text{ SAR per tCO}_2\text{e}.$$

Step 2: the annual cost line.

The fleet emits 15,000 tCO_2e per year (Example 17.1):

$$15{,}000 \times 93.75 = 1{,}406{,}250 \text{ SAR per year}.$$

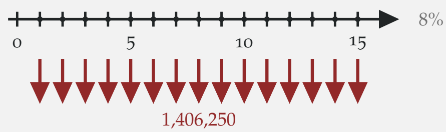

Figure 17.7. The median disclosed corporate carbon price as a 15-year cost line on the mine's genset fleet.

Step 3: discount it.

With $(P/A, 8\%, 15) = 8.5595$:

$$PW = 1{,}406{,}250\,(8.5595) = \boxed{12{,}036{,}797 \text{ SAR}}.$$

Step 4: per kilowatt-hour.

$$\frac{0.75}{1{,}000} \times 93.75 = 0.070 \text{ SAR per kWh},$$

so the diesel LCOE moves from 0.977 to $\boxed{1.047 \text{ SAR per kWh}}$. Reading the result against the chapter's earlier numbers: the median corporate price is real money at fleet scale, about 12 million SAR of present-worth liability, yet it still sits below the 149 SAR per tCO_2e flip price of Example 17.2, so it does not, by itself, hand the night block to solar. A firm that wants its internal price to drive that switch must choose a price above the flip, and the World Bank data shows such prices exist in implemented systems today.

What do the sources themselves conclude? The World Bank (2025) reports that carbon pricing has become a mainstream fiscal instrument, with all large middle-income economies either operating or considering direct carbon pricing, and average prices roughly doubling over the past decade while coverage grew from 12% to 28% of global emissions. CDP (2021) reports that internal carbon pricing correlates with other decarbonization action, that the practice grew 80% in five years, and that it is most common in the power sector, where 56% of disclosing companies already used one. For the working engineer, the operational summary is short: the carbon column of a project comparison now has public, checkable reference prices, in the same way interest-factor tables gave public, checkable discount arithmetic.

Insight. Note what the case study did and did not establish. Given a price, a tonnage, and a rate, the PW followed mechanically; that part is chapter 2. What the analysis cannot supply is the price itself: 25 USD is a median of disclosed corporate choices, not a law of nature, and the dashboard's implemented prices range from a few SAR to several hundred per tonne. This is why section 17.6 insisted on presenting carbon decisions as sensitivity sweeps with a flip price, rather than as single numbers computed at a price someone must pretend to know.

17.8 Chapter Summary

- A **carbon price** converts tonnes of CO_2e into SAR per year: emissions rate $\times$ price $=$ a cost line that discounts like any operating cost. A **regulated** price is a genuine cash flow; an **internal (shadow)** price changes rankings, never bank balances, and must be applied consistently to every alternative.
- The **emission factor** is engineering data (for diesel power, about $0.28 \times 2.68 \approx 0.75$ kg CO_2e per kWh); metered consumption, not brochures, sets it.
- The **flip price** p^* is the carbon price at which two alternatives tie: a break-even analysis (chapter 12) with the carbon price as the swept input. Present carbon-sensitive decisions as a one-way sweep with the flip price marked.
- **Life-cycle cost** (ISO 15686-5): $\text{LCC} = P_{\text{acq}} + PW_{\text{opr}} + PW_{\text{mnt}} + PW_{\text{eol}}$, with end-of-life positive for disposal and negative for recovery. The purchase price is often a small share of the LCC, and the cheap-to-buy option often loses.
- **End-of-life** terms are always estimated, then sometimes found negligible; omitting them is an audit finding, not a simplification.
- **Externalities** enter one of three ways: regulated price (cash flow), shadow price (comparison only, reported separately), or unpriced disclosure (a quantity column next to the money answer). Treating a shadow price as revenue manufactures money that will never arrive.
- The **circular economy** changes the last arrow of the diagram: recovery, second-life, and recycling channels raise the end-of-life value S_N or flip a disposal cost into a revenue. A higher S_N at one age can move the **economic service life** (chapter 16); a uniform premium at every age favors shorter lives, so the direction must be computed.
- Public references exist for all of it: the World Bank dashboard for regulated prices and coverage, CDP for corporate internal prices.

17.9 Exercises

These problems follow the chapter's order: carbon cost lines and the flip price at which a low-carbon option becomes the cheaper one, then life-cycle costing across acquisition, operation, and end of life, and finally circular end-of-life decisions in which a recovery price moves the economic service life.

Carbon as a cost line

Exercise 17.1. A crusher hall runs on diesel gensets that burn 900,000 liters of fuel per year, at 2.68 kg of CO_2e per liter. The firm adopts an internal carbon price of 120 SAR per tCO_2e. Find the annual carbon cost line and its present worth over the gensets' remaining 8-year life at a MARR of 10%.

Exercise 17.2. A cement plant must choose between two kilns for the same duty. Kiln F (fuel oil) has an annual equivalent cost of 480,000 SAR per year and emits 3,000 tCO_2e per year. Kiln E (electric, supplied under a renewable power contract) has an annual equivalent cost of 615,000 SAR per year and emits 300 tCO_2e per year. Find the internal carbon price at which the choice flips, and state the decision rule.

Life-cycle cost

Exercise 17.3. Two motors can drive the same conveyor for 8 years at a MARR of 12%. Motor S (standard) costs 12,000 SAR, uses 6,500 SAR of energy per year, and costs 800 SAR to dispose of at year 8. Motor P (premium efficiency) costs 18,000 SAR, uses 5,200 SAR of energy per year, and a recycler pays 600 SAR for it at year 8. Compute both life-cycle costs and state the decision.

Exercise 17.4. In a life-cycle cost analysis under the ISO 15686-5 breakdown, which cost group is most often omitted in practice, and why is the omission an error even when the discounted amount is small?

(A) Acquisition, because it happens before operations begin.

(B) Operation, because it is spread over many years.

(C) Maintenance, because it is uncertain.

(D) End-of-life, because it is distant and belongs to whoever holds the asset last.

Circular end-of-life

Exercise 17.5. A conveyor drive costs 30,000 SAR at $i = 10\%$. Its market value and operating cost by age are:

keep for N (years)	1	2	3
market value S_N (SAR)	21,000	15,000	10,000
operating cost OC_N (SAR)	3,000	4,500	6,500

(a) Build the $AEC(N)$ table and find the economic service life. (b) A remanufacturer's take-back program pays 19,000 SAR for 2-year-old drive cores (and nothing extra at other ages). Recompute and state the new economic service life.

Exam-style problems

The following problems are written in the Major Exam format: a scenario, lettered parts with point values, and full work expected. Classify the situation before computing, write the factor notation before substituting numbers, box each final answer with its units, and end with a decision sentence.

Exercise 17.6. Pricing carbon into compressed air at Najd Copper. The mill needs a new compressor for 10 years of service; the MARR is 10%, and do-nothing is not admissible. **Compressor D** (diesel-driven): first cost 200,000 SAR, salvage 20,000 SAR at year 10, fuel and upkeep 90,000 SAR per year, emissions 240 tCO_2e per year. **Compressor E** (electric, on the mine's solar supply): first cost 420,000 SAR, salvage 30,000 SAR at year 10, energy and upkeep 62,000 SAR per year, emissions 25 tCO_2e per year. (a) (*8 pts*) Compute each option's annual equivalent cost with no carbon price and state the choice. (b) (*8 pts*) The board adopts an internal carbon price of 150 SAR per tCO_2e. Recompute and state the choice. (c) (*6 pts*) Find the flip price and write the recommendation in one sentence.

Exercise 17.7. Life-cycle cost of two thickener drives at Wadi Phosphate. A thickener drive must serve for 12 years; the MARR is 8%. **Drive A**: first cost 150,000 SAR; O&M 28,000 SAR per year; a gearbox overhaul of 40,000 SAR at the end of year 6; removal and disposal cost 18,000 SAR at year 12. **Drive B**: first cost 230,000 SAR; O&M 17,000 SAR per year; no overhaul; removal and disposal cost 10,000 SAR at year 12. (a) (*10 pts*) Compute both life-cycle costs. (b) (*4 pts*)

State the choice and the margin. (c) (*6 pts*) A recycler claims it could pay for Drive A's materials at year 12 instead of A paying for disposal. How large would the year-12 recovery payment have to be to reverse the choice, and is that figure plausible?

Assessing outside recommendations

The two problems below present finished analyses produced by others. In each, the factor readings and the arithmetic are correct; the flaw is in the method. For each problem, (a) decide whether to accept the recommendation, (b) identify each error or omission precisely, and (c) produce the corrected numbers.

Exercise 17.8. An AI compares two filter presses and skips the ending. Najd Copper needs one of two filter presses for 10 years at a 10% MARR. **Press X**: 300,000 SAR, O&M 40,000 SAR per year; its contaminated liners make it hazardous plant at retirement, with a licensed-disposal cost of 90,000 SAR at year 10. **Press Y**: 360,000 SAR, O&M 36,000 SAR per year; the vendor's take-back program pays 15,000 SAR at year 10. An AI assistant produced the analysis below.

> $\text{LCC}_X = 300{,}000 + 40{,}000\,(P/A, 10\%, 10) = 300{,}000 + 40{,}000\,(6.1446) =$ 545,784 *SAR.* $\text{LCC}_Y = 360{,}000 + 36{,}000\,(6.1446) = 581{,}206$ *SAR. Press X has the lower life-cycle cost. Recommendation: buy Press X.*

(a) (*4 pts*) Should the firm accept the recommendation? (b) (*8 pts*) Identify the error precisely. (c) (*8 pts*) Produce the corrected comparison and the correct choice.

Exercise 17.9. A consultant books a shadow price as revenue. Wadi Phosphate is offered a waste-heat recovery unit: investment 2,500,000 SAR, fuel savings 380,000 SAR per year for 10 years, no salvage, MARR 10%. The kingdom-of-record has no carbon tax and no announced plan for one. The unit would avoid 1,200 tCO_2e per year. A consultant submits the memo below.

> *Fuel savings:* $380{,}000\,(P/A, 10\%, 10) = 2{,}334{,}948$ *SAR. Carbon benefit: at the social cost of carbon, 400 SAR per tonne, the unit earns* $1{,}200 \times 400 = 480{,}000$ *SAR per year, worth* $480{,}000\,(6.1446) = 2{,}949{,}408$ *SAR. Total NPW* $= -2{,}500{,}000 + 2{,}334{,}948 + 2{,}949{,}408 = +2{,}784{,}356$ *SAR. The project nearly doubles its money. Recommendation: proceed.*

(a) (*4 pts*) Should the firm accept the recommendation as written? (b) (*8 pts*) Identify each error precisely. (c) (*8 pts*) Produce the corrected presentation, including the break-even carbon price, and state a defensible recommendation.

References

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