

Design Challenge: A Solar Still That Runs on the Water Cycle

Learning target: I can analyze test data from several solar still prototypes, combine their best features into an improved design, plan the next test, and justify my choices with the criteria, the constraints and the science of evaporation, condensation and gravity.

Transfer and design

About 50 min

Pairs

MS-ETS1-3 · assesses

MS-ETS1-4 · practice

MS-ESS2-4 · supports

engineering design

data analysis

writing

Standards connections

MS-ETS1-3 (assesses): Students analyze side-by-side test data from six prototypes, identify which feature of each one helped, and combine the best characteristics into a new design, which is the PE as written.

MS-ETS1-4 (practice): Students plan an iterative test of their combined design, naming the variable to change, what to hold constant and what data to collect; they do not build or run it here, so this is practice toward the PE rather than full evidence.

MS-ESS2-4 (supports): MS-ESS2-4 is a California Grade 6 PE revisited in this lesson. The still is a miniature water cycle: the sun's energy drives evaporation below boiling, cooling at the cover drives condensation, and gravity drains the drops. Explaining the device with those drivers applies the model; it does not produce a model of Earth's water cycling.

Purpose: extend · **Time:** about 50 minutes · **Format:** pairs

Answers with reasoning

The design brief

A school in a dry coastal town wants a small **solar still** for its emergency kit: a device that uses only sunlight to turn salty or muddy water into clean drinking water. A solar still is a shallow basin of dirty water under a clear cover. Sunlight warms the water, water vapor rises, the vapor condenses on the cooler underside of the cover, and the drops run down the cover into a clean trough. Salt, mud and most germs stay behind in the basin.

Criteria and constraints — Criteria (what a good design does): C1: produces at least **400 mL** of clean water per sunny day. C2: is easy to carry: mass **1.5 kg or less**. C3: is simple enough for a student to set up in five minutes. **Constraints (limits that cannot be broken):** K1: materials cost **\$12 or less**. K2: uses **no electricity or fuel**. K3: fits in a box 60 cm × 40 cm × 30 cm. K4: the water never needs to boil (no flame and no boiling-hot parts).

The test report

Last year's class built six prototypes and tested them side by side on the same clear day, each starting with 2.0 L of salt water spread about 1 cm deep in a shallow basin. The clear covers were thin plastic film. The output is the clean water collected from sunrise to sunset. The warmest basin water measured all day, in prototype D, was **58 °C**.

Solar still prototypes tested on one clear day (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Prototype	Basin liner	Cover	Cover tilt	Insulation under basin	Output (mL/day)	Cost (\$)	Mass (kg)
A	white plastic	clear film	flat (0°)	none	180	6	0.8
B	black plastic	clear film	flat (0°)	none	310	7	0.9
C	black plastic	clear film	20°	none	390	8	1.0
D	black plastic	clear film	20°	foam board	460	11	1.3
E	black plastic	clear film	45°	foam board	410	12	1.4
F	black plastic	black (opaque) film	20°	foam board	40	11	1.3

Simulated data for teaching. The pattern (dark basin, tilted clear cover and insulation each raising output; an opaque cover killing it) matches how real small stills behave; actual outputs vary with weather.

Part A: Analyze the tests

1. Check each prototype against criterion C1, criterion C2 and constraint K1. Write yes or no in each cell, then yes or no in the last column.

Answer: A: no (180), yes (0.8), yes (\$6); no. B: no (310), yes, yes; no. C: no (390), yes, yes; no. D: yes (460), yes (1.3), yes (\$11); yes. E: yes (410), yes (1.4), yes (\$12, at the limit); yes. F: no (40), yes, yes; no. Only D and E meet C1, C2 and K1.

Why: C fails C1 by 10 mL; E meets K1 exactly at \$12. Both D and E pass.

Also acceptable: A student who flags E as 'passes, but with no cost margin' is reading the constraint well.

- All eighteen cells correct
- D and E identified as the only passing prototypes

2. Prototypes A and B differ only in the basin liner. Calculate the increase in output from A to B in mL and as a percent of A's output. Explain why a black liner helps, using the word *energy*.

Answer: Increase: $310 \text{ mL} - 180 \text{ mL} = 130 \text{ mL}$. Percent: $130 \div 180 = 0.722$, about 72 percent. A black liner absorbs more of the sunlight's energy instead of reflecting it, so the water gains more energy, its molecules move faster, and more of them escape as vapor.

Why: Arithmetic plus the absorption-of-energy mechanism. White surfaces reflect much of the light.

Also acceptable: Accept 72 or 72.2 percent.

3. Compare the pairs B and C, then C and D. For each pair, name the one feature that changed, the change in output in mL, and a reason the feature helped. (Think about where the drops go on a flat cover, and where the basin's energy goes without insulation.)

Answer: B to C: the cover was tilted from flat to 20° ; output rose $390 - 310 = 80 \text{ mL}$. On a flat cover, condensed drops hang underneath and fall back into the salty basin; on a tilted cover, gravity pulls the drops sideways and down the slope into the trough, so more of the condensed water is collected. C to D: foam insulation was added under the basin; output rose $460 - 390 = 70 \text{ mL}$. Without insulation the warm basin loses energy to the cold ground beneath it; insulation keeps that energy in the water, so the water stays warmer and evaporates faster.

Why: Each pair isolates one feature. The tilt reason is gravity delivering the drops; the insulation reason is retaining energy.

Also acceptable: Accept 'drops drip back into the dirty water on a flat cover.'

- Correct feature and output change for each pair
- Tilt explained through gravity moving drops to the trough
- Insulation explained through keeping energy in the water

4. D and E differ only in cover tilt, yet the steeper 45° cover produced **less** water. What does this tell you about 'more of a good thing'? Suggest one physical reason the steeper cover might have hurt.

Answer: Output fell from 460 to 410 mL (50 mL less), so a feature that helped at 20° did not help more at 45° : there is a best amount, and past it the feature starts to cost something. Possible reasons: the taller 45° cover encloses more air and has more surface, so it loses more energy to the outside and the inside stays cooler; the steep cover shades part of the basin when the sun is low; or the drops run so fast they splash past the trough. Any one physically reasonable reason earns credit.

Why: The engineering lesson is the optimum; the physics reason is secondary and several are acceptable.

Also acceptable: Accept 'the cover is bigger and more expensive but does not add light.'

- States that more tilt made output worse (an optimum exists)
- One physically reasonable cause

5. Prototype F is identical to D except that its cover is opaque, and it produced only 40 mL. What does F prove about where the still's energy comes from? What second job does the clear cover do besides letting light in?

Answer: F proves the still's energy comes from sunlight passing through the cover to the water: with an opaque cover, almost no light reaches the basin, the water barely warms, and almost no vapor forms (40 mL). The clear cover's second job is to be the cool surface where vapor condenses: it is cooler than the basin water because the outside air cools it, so vapor touching it gives off energy and turns back to liquid.

Why: Two functions: transmit sunlight (energy in) and provide a cooler condensation surface (energy out).

Also acceptable: Accept 'the cover also traps the vapor so it cannot blow away' as an additional job.

- Energy enters as sunlight through the clear cover
- Cover serves as the cool condensing surface

6. The warmest water in any basin was 58 °C, yet prototype D produced 460 mL of clean water. Explain the three water cycle steps inside the still, naming the driver of each (the sun's energy, cooling, or gravity), and explain why the salt does not travel with the water.

Answer: Step 1, evaporation (sun's energy): sunlight warms the basin water; even at 58 °C, far below boiling, the fastest molecules at the surface escape as vapor. Step 2, condensation (cooling): the vapor reaches the underside of the cover, which the outside air keeps cooler than the basin; the vapor gives off energy, its molecules slow and stick together as liquid drops. Step 3, collection (gravity): the drops grow, and gravity pulls them down the tilted cover into the trough and the container. Salt stays behind because only water molecules leave the liquid as vapor; salt does not evaporate at these temperatures, so it remains in the basin, which gets saltier as the day goes on.

Why: Three steps with three drivers, plus the explanation that evaporation separates water from dissolved salt. This is the water cycle in a box.

Also acceptable: Accept 'the same reason ocean water is salty but rain is fresh.'

- Evaporation below boiling, sun's energy
- Condensation at the cooler cover, cooling
- Drops drained by gravity
- Salt does not evaporate, so it stays in the basin

Part B: Combine the best features and plan the next test

7. Draw your improved still as a side view. Label the basin liner, the cover and its tilt, the insulation, the trough, and the collection container. Add arrows for sunlight, rising vapor, condensation on the cover, and drops running down to the trough, and label each arrow's driver (S, C or G).

Answer: A full-credit drawing shows, in side view: a black-lined basin on a foam board; a clear cover tilted about 20° (not 45°); a trough along the low edge of the cover leading to a container; sunlight arrows entering through the cover (S); vapor arrows rising from the water (S); condensation marked on the underside of the cover (C); drops running down the slope into the trough (G). Labels on all five required parts.

Why: Score the presence and correctness of the parts and the drivers; the design should match the data (black, tilted about 20° , insulated, clear).

Also acceptable: A student who draws a tilt between 20° and 30° with a note that the best angle is still being tested has understood q4.

- Five labeled parts
- Four labeled arrows with correct drivers S, S, C, G
- Features match the best tested data (black liner, clear cover, modest tilt, insulation)

8. List the features you kept from the tested prototypes and say which prototype's data justifies each one. Then name **one new change** you want to try that was not tested (ideas: a thicker or clearer cover, a shallower water depth, a reflector, a darker basin, a drip edge on the cover). Predict its effect and give a reason.

Answer: Kept features with evidence: black liner (A to B, +130 mL); clear cover (D versus F, 460 versus 40 mL); tilted cover near 20° (B to C, +80 mL; D to E shows 45° is worse); foam insulation (C to D, +70 mL). One new change with a predicted effect and reason, for example: a shallower water layer (1.0 L, about half a centimeter deep, instead of 2.0 L) should warm faster and evaporate more because the same sunlight heats less water; a reflector behind the basin should raise output because it adds light energy; a drip edge on the cover should keep drops from falling back; a thicker cover might reduce output because it absorbs some light but might also stay cooler. Any prediction with a sound physical reason earns credit.

Why: This is the combine-the-best-characteristics step of MS-ETS1-3; the new change must be untested and reasoned.

Also acceptable: A student who proposes removing the insulation to cut cost and mass, accepting lower output, is making a legitimate trade-off if they explain it.

- Each kept feature tied to a specific pair of prototypes
- One untested change
- Prediction with a physical reason

9. Plan the next test as an iterative test. State: the one variable you will change, the levels you will try (at least three), everything you will keep the same, how many days you will test, what you will measure and record, and what result would make you keep the change or drop it.

Answer: Example plan: Variable: cover tilt. Levels: 10°, 20°, 30° (three stills). Keep the same: black liner, clear film, foam insulation, 2.0 L of the same salt water at the same 1 cm depth, same location, tested on the same days side by side. Days: three clear days, recording each day separately and averaging. Measure and record: mL collected sunrise to sunset, maximum basin water temperature, weather notes. Decision rule: keep the tilt that gives the highest average output if it still meets cost and mass; if the differences are smaller than the day-to-day variation between identical stills, keep 20° and test a different variable next.

Why: A good iterative test changes one variable at several levels, controls the rest, repeats across days, and names the decision rule. Any variable from q8 is acceptable.

Also acceptable: A plan that tests two identical D stills first to measure how much output varies with no change is excellent experimental thinking.

- One variable with at least three levels
- Controlled features listed
- Repeated trials (days) named
- Data to record named
- A clear keep-or-drop rule

Part C: Justify the decision

10. Write a recommendation to the school. Say which tested prototype you would build today if there were no time for more testing, and why, checking it against every criterion and constraint. Then explain what your improved design (Part B) would add, what risk comes with it (cost, mass, or untested features), and how the next test would reduce that risk. End with one sentence on how the still depends on the same two drivers as Earth's water cycle.

Answer: Model response: Build D today. It meets C1 (460 mL, above 400), C2 (1.3 kg), C3 (a basin, a cover and a trough set up in minutes), K1 (\$11), K2 (sunlight only), K3 (a shallow basin with a 20° cover fits the box) and K4 (the water peaked at 58 °C, far below boiling; it is still hot enough to scald, so the still is emptied only after it cools). E also passes but costs \$1 more, makes 50 mL less, and leaves no cost margin. My improved design keeps D's black liner, clear cover, 20° tilt and insulation, and adds a shallower water layer (1.0 L instead of 2.0 L) to warm the water faster. The risk is that the change is untested: a shallower basin might run dry by afternoon, and if I add a reflector the cost could pass \$12. The next test (three depths, same everything else, three days) would show whether the gain is real and whether the basin lasts the day before we spend money on it. The still works for the same reason the water cycle works: the sun's energy lifts water out of the basin as vapor, and gravity brings the condensed drops back down to where we can collect them.

Why: Full credit: a tested prototype chosen and checked against all seven criteria and constraints; the improvement, its risk and the test that addresses the risk; and the closing link to the sun and gravity. A student who chooses E is acceptable if they justify it (for example, more steeply tilted covers shed dust) and acknowledge the cost limit.

Also acceptable: A student who recommends building two C stills instead of one D ($2 \times \$8 = \$16$, over budget) has missed K1; give partial credit for the reasoning about output.

- Chooses D (or E with justification) and checks every criterion and constraint
- Describes the improved design and its specific risk
- Explains how the next test reduces the risk
- Closes with the sun's energy and gravity as the shared drivers

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
Data analysis (Part A)	Every pairwise comparison isolates the right feature with the correct output change, and q1 identifies D and E as the only passing designs; reasons use energy, cooling and gravity correctly.	Comparisons correct; one reason is vague or one q1 cell is wrong.	Output changes read correctly but attributed to the wrong feature, or the criteria check is incomplete.	Data copied without comparison, or comparisons contradict the table.
Combined design (Part B, q7 and q8)	Design combines every feature the data support, each tied to the prototypes that justify it, plus one untested change with a reasoned prediction; drawing is complete with correct drivers.	Design combines the supported features; justification or the new change is thin; drawing missing one label.	Design includes a feature the data reject (opaque cover, 45° tilt, white liner) or omits a major one; drawing incomplete.	No design, or a drawing unrelated to the data.
Iterative test plan (q9)	One variable at three or more levels, controls listed, repeated days, data named, and a clear keep-or-drop rule.	Plan is sound but missing the decision rule or the repeated trials.	Plan changes more than one variable at a time, or does not say what to measure.	No plan, or a plan that cannot answer the design question.
Justification (q10)	Checks the chosen prototype against all seven criteria and constraints, names the specific risk of the improvement, links the next test to that risk, and connects the still to the sun and gravity.	Checks most criteria; risk or test link is general; water cycle link present.	Chooses a design with little reference to the criteria; no risk named.	No recommendation, or one that violates a constraint without noticing.

Teacher notes

The dataset is simulated but patterned on how small basin stills behave: dark absorbers, a modest cover tilt, insulation and a clear cover each matter, and real stills of this size yield a few hundred milliliters to about a liter per day. The 58 °C maximum is realistic and is the point of constraint K4: evaporation needs energy, not boiling (lesson pages printed 234 / PDF 270). Water at 58 °C can still scald skin within seconds, so in any real build the teacher handles water above 50 °C and students let the still cool before emptying it. The still mirrors the lesson's fog-catcher engineering strand (printed 242-243 / PDF 278-279), where iterative testing of net designs is described; the textbook's 'smaller holes collect the most water' is an oversimplification (there is a best mesh size, as there is a best tilt here), which q4 is designed to surface. MS-ETS1-3 evidence comes from Part A and q8; MS-ETS1-4 is practiced in q9 but not assessed because nothing is built. If students ask whether the still kills germs, say most are left behind in the basin but the still is not a complete purifier; emergency kits pair it with filtration or tablets. Extension arithmetic: $230 \times 0.46 \text{ L} + 135 \times 0.153 \text{ L} \approx 105.8 + 20.7 \approx 126 \text{ L}$ per still; $30 \text{ students} \times 2 \text{ L} \times 5 \text{ days} = 300 \text{ L}$, so storage from a month of mixed weather (about 10 L per still) implies roughly 30 stills, which is a useful shock about scale.

Scaffold offered to students: Read the table in pairs

The table is built so that most neighboring rows differ by exactly one feature: A to B changes only the liner, B to C only the tilt, C to D only the insulation, D to E only the tilt angle, D to F only the cover's clearness. When two rows differ by one thing, the change in output is caused by that one thing. Work down the table one pair at a time and write the feature and the output change in the margin before answering q2 to q5.

Extension: Cloudy-day budget

The town averages 230 clear days a year. Suppose prototype D makes 460 mL on a clear day and about a third of that on an overcast day. Estimate the yearly output of one D still in liters, then calculate how many stills the school would need to supply 2 L a day for each of 30 students during a 5-day emergency, if the stills had been collecting into storage for the previous 30 days of mixed weather. State every assumption and explain why a fog net might be a better partner for a solar still in a coastal town.