

Power for Cinder Ridge: Choosing an Energy Source With Criteria and Constraints

Learning target: I can define the criteria and constraints of a design problem, evaluate competing energy solutions against them with a systematic process, and justify a choice that depends on which resources the region actually has.

Transfer and design

About 50 min

Pairs

MS-ETS1-2 · assesses

MS-ETS1-1 · practice

MS-ESS3-1 · supports

engineering design

data analysis

writing

discussion

Standards connections

MS-ETS1-2 (assesses, evaluating competing design solutions with a systematic process): Students evaluate four competing energy designs with a pass/fail constraint check, a 30-year cost calculation and a decision matrix, then justify a recommendation against every criterion and constraint; that is the systematic evaluation this PE names, so the matrix and q6 are evidence toward it. The lesson's Hoover Dam section models the same move.

MS-ETS1-1 (practice): Part A asks students to turn the town's wishes into measurable criteria and constraints, including environmental limits, before any option is judged.

MS-ESS3-1 (supports): The winning option exists only because hot rock lies close to the surface at this plate-boundary site; the sheet asks students to say why the same choice would be impossible in a region without that geologic history.

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

Answers with reasoning

The brief from the Cinder Ridge town council — Cinder Ridge has 8,000 people and sits in a mountain valley on the slopes of a dormant volcano, 150 km from the nearest city. The town's old power line failed and will not be rebuilt. The council must choose one way to generate the town's electricity for the next 30 years. The town uses about 40 million kilowatt-hours (40 GWh) a year, and it must have power every hour of every day, including winter nights and dry summers. The council can spend at most \$130 million in total over the 30 years, counting construction, fuel and running costs. Cinder Creek, which runs through the valley, has a protected salmon run that must be able to pass upstream. The valley's farmland is the town's main income, so no option may take more than 1 square kilometer of it. The council also wants the option with the least air pollution that meets everything else.

Geology report (teaching data): A drilling survey found rock at 2 km depth under the town's north edge at 240 °C, with groundwater in cracked volcanic rock, because magma sits a few kilometers below the dormant volcano. Cinder Creek's flow drops to one-third of its spring value in late summer and in drought years. The valley gets about 2,100 hours of sunshine a year, but December and January together receive only about a fifth of the sunshine that June and July receive.

Four competing designs (teaching data)

1 Option A: Flash-steam geothermal plant

Two production wells and one injection well into the 240 °C rock. Output: 45 GWh a year, steady day and night in every season. Construction: \$60 million. Running cost: \$1.5 million a year. Land: 0.1 km² on rocky ground outside the farmland. Air pollution: very low. Risks: the first well might miss the hottest rock (a test well would cost \$4 million extra); if the plant pumps faster than the rock reheats the water, output falls over the years unless the injection well returns all the water.

2 Option B: Diesel generators

Four generators burning diesel fuel trucked 300 km from the coast. Output: up to 50 GWh a year, any hour, as long as fuel arrives. Construction: \$15 million. Fuel and running cost: \$5 million a year at today's prices. Land: 0.05 km². Air pollution: high; also the largest carbon dioxide release of the four. Risks: fuel prices can double; the mountain road closes for several days each winter, so the town must store fuel.

3 Option C: Hydroelectric dam on Cinder Creek

A 30 m concrete dam and reservoir 4 km upstream of town. Output: 32 GWh in an average year, but only 18 GWh in a dry year and much less in late summer. Construction: \$75 million. Running cost: \$1 million a year. Land: the reservoir floods 2 km² of the upper valley, of which 0.6 km² is farmland. Air pollution: very low. Risks: the dam blocks the salmon run unless a fish ladder is added (\$8 million, and ladders work only partly); the reservoir traps sediment that used to reach downstream fields.

4 Option D: Solar farm with batteries

Solar panels on the valley floor with a battery bank that stores power for the night. Output: 42 GWh in an average year, but December and January together produce only about 3 GWh, and the batteries hold enough for one night, not a week of winter storms. Construction: \$90 million. Running cost and battery replacement: \$1.2 million a year. Land: 1.2 km² of farmland (there is no flat rocky ground large enough). Air pollution: very low. Risks: a cloudy winter week would leave the town without power unless a backup is added.

Part A: Define the problem precisely

1. Turn each of the council's wishes into a precise, testable statement. A criterion is a goal the design is judged on; a constraint is a limit it must not break. Write at least one number or a clear yes/no test in every row.

Answer: Enough electricity: criterion; produces at least 40 GWh per year; from 'uses about 40 GWh a year.' Reliable every hour: criterion (or constraint); supplies the town's power every hour in winter and in a dry year, so output must not fall below what the town needs in any season or year type; from 'every hour of every day, including winter nights and dry summers.' Affordable: constraint; total 30-year cost of construction + fuel + running $\leq$ \$130 million; from the budget sentence. Salmon can pass: constraint; yes/no test: salmon can still migrate upstream past the project; from the protected-run sentence. Farmland protected: constraint; farmland taken $\leq$ 1 km²; from the farmland sentence. Least air pollution: criterion; of the options that meet everything else, pick the lowest air pollution; from the last sentence.

Why: The distinction between criteria (judged, can be better or worse) and constraints (hard limits) is the point of MS-ETS1-1. Reliability can be defended as either; what matters is a testable version.

Also acceptable: Accept 'reliable' as a constraint ('must never leave the town without power') if the measurable version is given.

- Each row labeled criterion or constraint with a defensible choice
- Each row has a number or a yes/no test
- Each row is traced to the brief

2. 'Reliable' is the hardest wish to measure. Explain why 'produces at least 40 GWh a year' is not enough by itself, and write the extra test that catches Option C's and Option D's weaknesses.

Answer: An annual total can hide months or years of shortage: Option C makes 32 GWh in an average year but only 18 in a dry year, and Option D makes 42 GWh a year but only about 3 GWh in December and January together and cannot cover a week of winter storms. The extra test: the option must supply the town's full demand in its worst month and its worst year without outside help (or: output in a dry year $\geq$ 40 GWh and output in every month $\geq$ the town's monthly need).

Why: This is the engineering habit of testing the worst case rather than the average.

Also acceptable: Accept 'must work in a dry year and in January' as the extra test.

- Explains that averages hide seasonal or dry-year shortfalls, citing C or D
- Writes a worst-month or worst-year test

Part B: Evaluate the four designs systematically

3. Calculate the 30-year total cost of each option: construction + (running cost per year $\times$ 30). For Option A include the \$4 million test well. For Option C include the \$8 million fish ladder. Show all four calculations and state which options stay within \$130 million.

Answer: A: \$60M + \$4M test well + (\$1.5M $\times$ 30) = \$64M + \$45M = \$109 million. B: \$15M + (\$5M $\times$ 30) = \$15M + \$150M = \$165 million. C: \$75M + \$8M ladder + (\$1M $\times$ 30) = \$83M + \$30M = \$113 million. D: \$90M + (\$1.2M $\times$ 30) = \$90M + \$36M = \$126 million. Within \$130 million: A, C and D. B is over by \$35 million.

Why: Straight multiplication and addition; the fuel cost is what makes diesel the most expensive despite the cheapest construction.

Also acceptable: Accept A = \$105 million if the student forgot the test well but shows the work, with a note; the conclusion about which options pass does not change.

4. Fill in the decision matrix with yes, no, or the pollution level, using the cards, the geology report and your q3 costs. In the last column write yes only if the option passes every constraint and meets the supply criterion in every season and every kind of year.

Answer: A: yes (45 GWh steady every season); yes (\$109M); yes (not on the creek); yes (0.1 km², rocky ground); low; passes: yes. B: yes (50 GWh any hour, if fuel stored); no (\$165M); yes; yes (0.05 km²); high; passes: no. C: no (18 GWh in a dry year, little in late summer); yes (\$113M); partly at best (ladder works only partly; without it, no); yes (0.6 km² farmland flooded); low; passes: no. D: no (about 3 GWh in Dec-Jan, batteries cover one night); yes (\$126M); yes; no (1.2 km² farmland); low; passes: no.

Why: Only A passes every constraint and meets the supply criterion in the worst season and year. The matrix should show that B fails on cost, C on reliability and salmon, D on winter supply and farmland.

Also acceptable: A student who marks C's salmon cell 'yes with ladder' must still fail C on dry-year supply; accept if the last column is 'no.'

- Costs match q3
- Supply column uses the worst case, not the average
- C's salmon cell notes the ladder works only partly
- Only A marked as passing everything

5. For each option that fails, name the single most serious failure and the card sentence that proves it.

Answer: B: cost, \$165 million over 30 years, from 'fuel and running cost: \$5 million a year' (also the high pollution). C: supply in a dry year, from 'only 18 GWh in a dry year and much less in late summer' (also the salmon run: 'the dam blocks the salmon run'). D: winter supply, from 'December and January together produce only about 3 GWh, and the batteries hold enough for one night' (also farmland: '1.2 km² of farmland').

Why: Students should name the decisive failure and quote the evidence; secondary failures are a bonus.

Also acceptable: For C, the salmon constraint is an acceptable 'most serious' failure; for D, the farmland constraint is acceptable.

- One serious failure per failing option
- Each tied to a card sentence or a calculated number

Part C: Recommend and justify

6. Write your recommendation to the council. State the option, show that it meets every criterion and constraint with numbers from your matrix, name its main risk and how the town should reduce that risk, and explain what the town gives up by not choosing the runner-up.

Answer: Model: 'Recommend Option A, the geothermal plant. It supplies 45 GWh a year, above the 40 GWh need, steadily day and night in every season and in dry years, so it passes the reliability test that C and D fail. Its 30-year cost is \$109 million including a test well, under the \$130 million limit that B breaks. It is not on Cinder Creek, so the salmon run is untouched, and it uses 0.1 km² of rocky ground, well under the 1 km² farmland limit. Its air pollution is very low, so among options that meet everything else it is also the cleanest. Main risk: the first well might miss the hottest rock, so drill the \$4 million test well first and commit to construction only if it confirms the 240 °C rock; the second risk is output falling if water is pumped faster than it is reheated, so the contract must require that all water be returned through the injection well and that pumping stay within the rate the survey shows the rock can sustain. By not choosing the runner-up, Option D, the town gives up a source with no drilling risk and spreads its risk less, but D would have taken 1.2 km² of farmland and left the town dark in cloudy winter weeks.'

Why: Full credit requires the option, numbers for every criterion and constraint, a named risk with a reduction, and the trade-off with a runner-up. Option D is the natural runner-up; C is acceptable if argued.

Also acceptable: A pair that recommends a hybrid (A plus a small solar array) with the arithmetic shown is giving an advanced answer; score it on the same criteria.

- Names Option A (or defends another choice against every constraint, which the data do not allow)
- Cites numbers for supply, cost, salmon, farmland and pollution
- Names the main risk and a specific way to reduce it
- States what is given up by rejecting the runner-up

7. Explain, using the geology report and what you know about how geothermal energy is distributed, why your recommended option is available to Cinder Ridge at all. Then say whether the same recommendation would work for a town on flat farmland 1,000 km from any plate boundary, and what that town's best option might be.

Answer: Geothermal power is possible here only because magma sits a few kilometers below the dormant volcano, so rock at 2 km is 240 °C and groundwater in the cracked volcanic rock is already hot. That is a feature of plate-boundary regions and volcanic areas; geothermal energy is unevenly distributed because hot rock is shallow only where magma is near the surface. A town on flat farmland 1,000 km from a plate boundary would find rock at 2 km at only about 60 to 70 °C, far too cool to flash into steam, so Option A would be impossible there. Its best option would depend on its own resources: a river for hydro (if fish and land allowed), good sunshine for solar with more land available, or a connection to a regional grid; it could not simply copy Cinder Ridge.

Why: This is the MS-ESS3-1 connection: the design space is set by the resource distribution, which is set by geologic processes.

Also acceptable: Accept an estimate of ordinary rock temperature at 2 km anywhere from 50 to 75 °C.

- Links the 240 °C rock to shallow magma at a volcanic or plate-boundary site
- States that the flat-farmland town lacks shallow heat, so geothermal would not work
- Suggests a plausible alternative tied to that town's own resources

8. Option A uses a renewable resource, but the card says output can fall over the years. Explain how the town could run the plant unsustainably, and what one rule in the plant's operating contract would prevent it.

Answer: The town could run the plant unsustainably by pumping hot water out faster than heat flowing up from the magma can reheat new water, or by letting the cooled water go instead of injecting it back, so the hot aquifer loses pressure and water and the field cools over the years. The contract rule: all produced water must be returned through the injection well, and the pumping rate must not exceed the sustainable rate measured in the survey (with a required cut if the well temperature or pressure starts to fall).

Why: Geothermal energy stays renewable because Earth's heat keeps flowing, but whether this plant's use is sustainable depends on its rate of use compared with replenishment; this closes the loop with W2 and W4.

Also acceptable: Accept 'monitor the temperature every year and reduce pumping if it drops' as the rule.

- Describes over-pumping or failure to reinject as the unsustainable practice
- Writes a specific rule that limits the rate or requires reinjection

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
Criteria and constraints (Part A)	All six rows are measurable, correctly labeled, traced to the brief, and the reliability test covers the worst month and worst year.	Five rows measurable and labeled; the reliability test is present but incomplete.	Rows restate the brief without numbers, or criteria and constraints are confused throughout.	Part A mostly blank.
Systematic evaluation (Part B)	All four 30-year costs correct with work shown; the matrix uses worst-case supply, every cell has evidence, and only A passes.	One arithmetic slip or one matrix cell unsupported; the final column is still correct.	Matrix filled from averages or impressions; two or more cells wrong.	No calculations; matrix blank or guessed.
Recommendation and justification (Part C)	Choice supported with numbers for every criterion and constraint, a named risk with a specific reduction, and the trade-off against the runner-up.	Choice supported with most numbers; risk or trade-off is thin.	Choice stated with general reasons and few numbers.	No recommendation, or one that breaks a constraint without acknowledging it.
Connection to resource distribution (q7, q8)	Explains why shallow hot rock exists here and not on distant farmland, and states a rate-based rule that keeps the geothermal use sustainable.	Explains the geologic reason or the sustainability rule well, the other only partly.	Mentions volcanoes or plate boundaries without connecting them to the design choice.	No connection made.

Teacher notes

All figures are teaching data, scaled to be realistic: 40 GWh a year for 8,000 people is about 5,000 kWh per person, typical for a small U.S. town with some industry; 240 °C at 2 km is a high-quality geothermal resource like those in volcanic regions; the solar winter-to-summer ratio of roughly one-fifth is realistic for a

mountain valley at mid-latitudes with winter cloud; diesel at \$5 million a year for about 50 GWh is in a realistic range for remote generation. The intended outcome is Option A, with the test well as the risk-reduction move and reinjection as the sustainability rule. Pairs that argue for a hybrid in the extension are doing the real engineering. Connect the matrix explicitly to the Hoover Dam story in the lesson: the team compared five dam types against criteria (storage, electricity, flood control) and constraints (cost, site, environment) and chose the arch-gravity design for that canyon; note that the textbook's claim that earth and rockfill dams cannot store as much water is a judgment for that site, not a general rule.

Scaffold offered to students: Fail fast, then compare

Engineers check constraints first, because a design that breaks a constraint is out no matter how good it is otherwise. Go down the matrix column by column: cost, salmon, farmland. Cross out any option that fails a constraint. Only then compare the survivors on the criteria (supply in the worst season and the worst year; pollution). For the cost column, write the multiplication on one line and the addition on the next: for example, \$15 million + (\$5 million $\times$ 30) = \$15 million + \$150 million = \$165 million.

Extension: Design the hybrid

Real towns rarely choose only one source. Design a two-source system for Cinder Ridge that costs no more than \$130 million over 30 years, meets the supply criterion in every season, and respects every constraint. Scale the options as you wish (for example, half-size solar at half the cost and land, with a small geothermal plant), show the cost arithmetic, and explain which weakness of each source the other one covers. Then write one sentence on what the Hoover Dam team would recognize in your process.