

Fuel for the Island Ferry: Choosing a Biomass Source

Learning target: I can define criteria and constraints for a renewable ferry fuel, score four biomass sources against them with data, recommend a solution or a combination, and justify it by tracing the fuel's matter and energy back to photosynthesis.

Transfer and design

About 50 min

Pairs

MS-ETS1-1 · assesses

MS-ETS1-2 · assesses

MS-LS1-6 · supports

engineering design

data analysis

writing

Standards connections

MS-ETS1-1 (assesses): Students must write the criteria and constraints of the ferry-fuel problem with numbers or tests, taking into account the island's land, food crops and budget, which is the precision this PE asks for.

MS-ETS1-2 (assesses): Students score four competing biomass sources in a systematic matrix against their own criteria and constraints and choose or combine solutions, producing evidence toward this PE.

MS-LS1-6 (supports): Every candidate fuel is biomass whose stored chemical energy was captured from sunlight by producers; the justification asks students to trace that matter and energy, which is background for the PE rather than a full explanation of photosynthesis.

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

Answers with reasoning

The brief from the Isla Verde council — 'Our ferry is the only link to the mainland. It burns 40,000 liters of diesel a year, all shipped in. We want to replace as much of that as we can with a fuel made here, from the island's own plants or plant waste. Rules: the fuel must be made on the island; any plant material we use must grow back at least as fast as we use it; no farmland now growing food may be switched to fuel crops; and the setup cost must not exceed \$350,000. We would like the fuel to pack as much energy as possible into each kilogram so the ferry can carry less, to cost as little as possible per liter, and to need as few changes to the ferry's engine as possible.'

Energy stored per kilogram of fuel (typical rounded values)

Fuel	Energy per kilogram (megajoules)	Works in the ferry's diesel engine?
Diesel (fossil, shipped in)	43	yes
Biodiesel (made from plant or waste oils)	37	yes, blended, with minor changes
Ethanol (made from plant sugars)	27	no; engine must be converted
Dry wood chips (burned directly)	17	no; not a liquid fuel

Reference values rounded from standard fuel tables. A megajoule (MJ) is a unit of energy; a liter of diesel holds about 36 MJ.

Four candidate biomass sources on Isla Verde (teaching dataset)

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

Candidate	Source and process	Fuel type made	Diesel-equivalent liters per year	Land used	How fast the source regrows	Takes farmland from food?	Setup cost (\$)	Cost per diesel-equivalent liter (\$)
A	Used cooking oil collected from the island's restaurants and homes	Biodiesel	12000	none	continuous (it is waste)	no	60000	1.2
B	Fast-growing energy grass planted on 20 hectares of vegetable farmland, cellulose broken into sugar, sugar made into alcohol	Ethanol	50000	20 ha of farmland	every year	yes	250000	1.6
C	Thinnings from the island's 300-hectare forest, cellulose broken into sugar, sugar made into alcohol; harvest 7.5 ha per year, forest regrows in 40 years	Ethanol	11000	7.5 ha of forest per year	each patch in 40 years; whole forest replaces 7.5 ha per year	no	180000	2.0

Candidate	Source and process	Fuel type made	Diesel-equivalent liters per year	Land used	How fast the source regrows	Takes farmland from food?	Setup cost (\$)	Cost per diesel-equivalent liter (\$)
D	Algae grown in shallow ponds on 2 hectares of bare rocky ground, oil pressed from the algae	Biodiesel	200000	2 ha of rocky ground	continuous (harvested weekly)	no	2800000	3.5

Simulated data for teaching, invented to be realistic for a small island. 'Diesel-equivalent liters' means the fuel has already been converted into the number of liters of diesel it could replace, so the candidates can be compared directly.

Part A: Define the problem precisely

- Write three **criteria** from the brief (things a good solution does as well as possible). Each must include a number or a clear way to measure it, for example 'covers the largest possible share of the 40,000 L need.'

Answer: Examples: (1) Covers the largest possible share of the 40,000 L per year need, measured as a percent. (2) Stores as much energy per kilogram as possible, measured in MJ per kg from the fuel table. (3) Costs as little as possible per diesel-equivalent liter, in dollars. A fourth acceptable criterion: needs the fewest changes to the ferry's engine.

Why: Criteria are 'as well as possible' goals; each needs a measurable form.

Also acceptable: Accept 'uses as little land as possible' as a criterion if measured in hectares.

- Three criteria from the brief
- Each has a number, unit or measurable test

- Write the four **constraints** from the brief (limits a solution must not break), each with its limit. Then add one constraint of your own that the council forgot and explain why it matters.

Answer: From the brief: (1) the fuel must be made on the island; (2) the plant source must regrow at least as fast as it is used; (3) no farmland now growing food may be switched to fuel; (4) setup cost must not exceed \$350,000. A fifth of the student's own, for example: the fuel must be safe to store near the harbor; the processing plant must not pollute the island's water; the fuel must be ready within two years; the fuel must work in winter temperatures.

Why: Constraints are limits that cannot be broken. The added constraint must be a real limit with a reason.

Also acceptable: Accept 'the ferry must still be able to make its trips' as an added constraint.

- All four brief constraints with their limits
- One added constraint with a reason

3. Explain the difference between a criterion and a constraint using 'regrows at least as fast as it is used' and 'costs as little as possible per liter' as your two examples.

Answer: 'Regrows at least as fast as it is used' is a constraint: a candidate either meets it or is out; there is no 'more' or 'less' of passing. 'Costs as little as possible per liter' is a criterion: every candidate has some cost, and the question is how well it does compared with the others. Constraints decide who is allowed to compete; criteria decide who wins.

Why: The pass-or-fail versus better-or-worse distinction is the heart of ETS1-1.

Also acceptable: Accept 'a constraint is a rule; a criterion is a goal' with the two examples correctly placed.

- Regrowth identified as pass-or-fail
- Cost identified as a matter of degree
- States the general difference

Part B: Score the candidates

4. Complete the table. For the percent column, divide the candidate's liters by 40,000 and multiply by 100; show one calculation below the table. For the last column, check each candidate against every constraint from q2.

Answer: A: 12,000 L; $12,000 \div 40,000 \times 100 = 30$ percent; biodiesel 37 MJ/kg; breaks no constraint. B: 50,000 L; 125 percent; ethanol 27 MJ/kg; breaks the no-food-farmland constraint (uses 20 ha of vegetable farmland). C: 11,000 L; 27.5 percent; ethanol 27 MJ/kg; breaks no constraint (7.5 ha harvested per year, forest regrows $300 \div 40 = 7.5$ ha per year, so it keeps pace). D: 20,000 L; 50 percent; biodiesel 37 MJ/kg; breaks no constraint (\$280,000 is under \$350,000).

Why: B is the only constraint breaker. Students sometimes flag C for the 40-year regrowth; the check is that harvest (7.5 ha per year) equals the regrowth rate ($300 \text{ ha} \div 40 \text{ years} = 7.5 \text{ ha per year}$), so it is sustainable.

Also acceptable: Accept C marked as 'borderline' if the student shows the $7.5 = 7.5$ calculation.

5. Score each candidate on each criterion using the scales given, total the scores, and record whether the candidate passes every constraint. A high score does not rescue a candidate that breaks a constraint.

Answer: A: share 1 (30 percent), energy 2 (37), cost 2 (\$1.20), engine 2 (minor); total 7; passes constraints: yes. B: share 2 (125 percent), energy 1 (27), cost 1 (\$1.60), engine 1 (conversion); total 5; passes: no (food farmland). C: share 1 (27.5 percent), energy 1 (27), cost 1 (\$2.00), engine 1 (conversion); total 4; passes: yes. D: share 2 (50 percent), energy 2 (37), cost 0 (\$3.50), engine 2 (minor); total 6; passes: yes.

Why: With the given scales, A scores highest among candidates that pass, D second, C third; B's high share cannot rescue it. The scales are fixed so the matrix is checkable.

Also acceptable: If a student rounds C's 27.5 percent up to a 1 or down to a 0 on the share criterion, accept either with the number shown; the scale says 25 to 40 earns 1.

6. No single candidate that passes every constraint covers more than half the need, so consider combinations. For each of these pairs, add the liters, compute the percent of the need, and add the setup costs: A + C, A + D, C + D, and A + C + D. Which combinations stay within the \$350,000 setup limit?

Answer: A + C: $12,000 + 11,000 = 23,000$ L = 57.5 percent; setup $\$60,000 + \$180,000 = \$240,000$ (within limit). A + D: $12,000 + 20,000 = 32,000$ L = 80 percent; setup $\$60,000 + \$280,000 = \$340,000$ (within limit). C + D: $11,000 + 20,000 = 31,000$ L = 77.5 percent; setup $\$180,000 + \$280,000 = \$460,000$ (over the limit). A + C + D: $43,000$ L = 107.5 percent; setup $\$520,000$ (over the limit). Within the \$350,000 limit: A + C and A + D.

Why: Liters and costs add; percent is recomputed from the new total. Only two combinations survive the budget constraint, and A + D covers far more of the need.

Also acceptable: Accept percents rounded to whole numbers (58, 80, 78, 108).

Part C: Decide and justify

7. Recommend one candidate or one combination to the council. Justify it with: (1) the constraints it passes and the one candidate you rejected for breaking a constraint; (2) at least three numbers from your tables; (3) one trade-off you accepted and why; and (4) one sentence tracing where the energy in your fuel originally came from and how it got into the plant material.

Answer: Model recommendation: A + D (used cooking oil plus algae ponds). (1) It passes all four constraints: made on the island, both sources renew continuously, no food farmland is used, and setup is \$340,000, under the \$350,000 limit; B was rejected because it converts 20 ha of vegetable farmland, which breaks a constraint regardless of its 125 percent coverage. (2) Numbers: A + D supplies 32,000 L, 80 percent of the 40,000 L need, compared with 57.5 percent for A + C; both fuels are biodiesel at 37 MJ/kg, the highest of the biofuels, and need only minor engine changes. (3) Trade-off accepted: D's fuel is expensive at \$3.50 per liter and the algae method is new, so the council pays more per liter and takes some risk in exchange for covering 50 percentage points more of the need than A alone (80 percent versus 30 percent); a cautious council could start with A now (\$60,000, 30 percent) and add D after a trial. (4) Energy trace: the chemical energy in both fuels was captured from sunlight by producers, the algae in the ponds and the crops that became cooking oil, during photosynthesis, when light energy was stored in sugars and then in the oils the plants and algae built from them.

Why: A + D is the strongest answer under these constraints, but A alone (lowest cost and risk) or A + C (cheaper, lower coverage) are defensible if the trade-off is stated honestly. Full credit requires all four justification parts with numbers.

Also acceptable: A recommendation of A alone is acceptable if the student explains that it covers only 30 percent but minimizes cost and risk and could be expanded later. A recommendation of B is not acceptable because it breaks a constraint, but credit the matrix work.

- Names a candidate or combination that passes every constraint
- Explains why B is rejected on a constraint
- Uses at least three numbers from the tables
- States a trade-off and why it is accepted
- Traces the fuel's energy to sunlight captured by producers through photosynthesis

8. A council member says: 'Great, biofuel means the ferry will stop putting carbon dioxide into the air.' Is that right? Explain what burning the biofuel does release and what is actually different from burning shipped-in diesel.

Answer: Not right. Burning any biofuel releases carbon dioxide, because the fuel is made of carbon-containing molecules and burning combines them with oxygen. The difference from shipped-in diesel is where the carbon came from: the biofuel's carbon was taken out of the air by producers through photosynthesis recently, and the plants or algae that replace the harvested ones take it up again, whereas diesel's carbon has been underground for millions of years and burning it adds carbon that was not in today's air. Biofuel also avoids shipping fuel to the island.

Why: This corrects the common belief that biofuel is carbon-free. The answer should name carbon dioxide as a product of burning and explain the recent-capture difference.

Also acceptable: Accept 'it still makes carbon dioxide, but the plants took that carbon from the air in the first place.'

- States that burning biofuel releases carbon dioxide
- Explains the difference as carbon recently captured by producers versus fossil carbon

9. Sketch the path of matter and energy for your recommended fuel, from the sun to the ferry's propeller. Use solid arrows for matter (carbon dioxide, water, plant material, oil or sugar, fuel, exhaust) and dashed arrows for energy (light, chemical energy in the plant, chemical energy in the fuel, energy of motion). Label every arrow.

Answer: A complete sketch shows: a dashed arrow from the sun to the producer (algae or oil crop) labeled 'light energy'; solid arrows into the producer labeled 'carbon dioxide' and 'water'; a solid arrow from the producer to 'oil' or 'plant material' with a dashed arrow alongside labeled 'chemical energy stored'; a solid arrow to 'biodiesel' at the island plant; a solid arrow from the fuel to 'exhaust: carbon dioxide and water' at the engine with a dashed arrow labeled 'energy of motion' to the propeller. For A, the chain passes through 'cooking oil used in kitchens' before the fuel step.

Why: The sketch is credited for correct solid-versus-dashed use, the carbon dioxide and water inputs at the producer, the carbon dioxide output at the engine, and energy shown as captured, stored and released rather than used up.

Also acceptable: Accept a sketch for whichever candidate the student recommended.

- Light energy as a dashed arrow into a producer
- Carbon dioxide and water as solid arrows into the producer
- Chemical energy stored in plant material and fuel shown as dashed arrows
- Exhaust carbon dioxide shown leaving the engine
- All arrows labeled

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
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Criteria and constraints (Part A)	Three criteria with measurable forms, four brief constraints with their limits, one well-reasoned added constraint, and the criterion-versus-constraint distinction explained with both examples placed correctly.	All items present; one criterion lacks a measurable form or the added constraint has no reason.	Criteria and constraints mixed up in one or two places, or fewer than four constraints.	Lists are missing, or criteria and constraints are not distinguished.
Use of data (Part B)	Percent, energy and constraint columns correct for all four candidates; score matrix totals correct; all four combinations computed with the budget check.	One arithmetic slip, or one combination missing, with the method otherwise correct.	Several errors, or scores assigned without using the given scales.	Tables mostly blank or unrelated to the data.
Decision and justification (Part C)	Recommends a constraint-passing solution, rejects B on its constraint, cites three or more numbers, states an honest trade-off, and explains the choice in terms of criteria the council named.	Recommendation and numbers present; trade-off vague or the rejected candidate not explained.	Recommendation stated with one number or with reasoning that ignores a constraint.	No recommendation, or a recommendation that breaks a constraint without acknowledging it.
Science connection	Traces the fuel's energy to sunlight captured by producers, keeps matter and energy distinct in the sketch, and correctly states that burning biofuel releases carbon dioxide while explaining the recent-capture difference.	Energy traced to photosynthesis; sketch mostly correct; the carbon dioxide point partly stated.	Mentions photosynthesis without tracing; sketch confuses matter and energy arrows; or claims biofuel releases no carbon dioxide.	No connection to photosynthesis.

Teacher notes

The energy-per-kilogram values are standard rounded figures (diesel about 43 MJ/kg, biodiesel about 37, ethanol about 27, dry wood about 17) and are real reference data; the island dataset is simulated and built so that the arithmetic is clean and the decision has a real tension: the only candidate that covers the whole need breaks the food-farmland constraint, and the best combination (A + D) sits just under the budget. Candidate C's sustainability check ($300 \text{ ha} \div 40 \text{ years} = 7.5 \text{ ha per year harvested}$) is deliberately borderline so that students must compute rather than guess. This sheet corrects two simplifications in the textbook's jet-fuel spread: 'efficient' is replaced by energy per kilogram, and the sheet does not claim biofuels are low-cost; as of 2026 biofuels generally cost more than fossil fuels, which is why cost is a criterion here. Alcohol from cellulose must be converted or the engine modified, which the engine-change criterion captures. Keep the photosynthesis connection at the level of capturing and storing energy and tracing carbon; do not open the biochemistry.

Scaffold offered to students: Constraints first, then scores

Engineers check constraints before they score anything, because a candidate that breaks a constraint is out no matter how well it scores. Go down the brief's four rules and ask each candidate 'does this break the rule?' before you fill in the score table. Then, for combinations, remember that liters add and setup costs add, but the percent of need must be recomputed from the new total: $(\text{total liters} \div 40,000) \times 100$.

Extension: The second ferry

Five years later the island adds a second ferry, doubling the need to 80,000 liters per year, and the council allows 10 hectares of farmland to be used for fuel after all. Reopen the problem: which constraints changed, which candidates re-enter, and does your recommendation change? Write a short memo with the new numbers. Then explain why a decision that was best under the old constraints can stop being best when the constraints move, even though none of the data about the candidates changed.