

The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and that elucidate difficult concepts. Manuscripts should not exceed ten double-spaced pages if possible and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

AN "OPEN-ENDED ESTIMATION" DESIGN PROJECT FOR THERMODYNAMICS STUDENTS

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The project is "open-ended" when the students ask if only one design is right, and an "estimation" will suffice when they cannot find an exact value; the descriptive title for the project intentionally reinforces the expectation of this assignment for the student. The project is a preliminary design to evaluate methods of generating electricity for a resort island. As seen in the accompanying press release (Table 1), written in the form of an advertisement for tourism, a tropical island abundant in leisure activities is described; thinly veiled within the ad are various resources that could be used to produce electrical energy.

This design effort is assigned in a first course in thermodynamics offered by the Department of Chemical Engineering at the University of Missouri at Columbia. All the material typically contained in a "classical thermodynamics" course (first law, second law, and power cycles) is covered in this 15-week semester-long course, and most of the students are first-semester Juniors, having recently completed an introductory chemical engineering course covering material and energy balances. Although the students are still in the beginning stages of their chemical engineering coursework, this project meets the need of providing some early design opportunity in the curriculum. The project also incorporates role playing and decision making, two important elements of active learning^[1] and critical thinking.^[2]

PROJECT ORGANIZATION

The overall objective of this preliminary design is to recommend methods of energy generation that meet the elec-

tricity needs of the island, with some assessment of environmental and safety concerns. The methods proposed by students to date are listed in Table 2.

Organization of the project is shown schematically in Figure 1, and the project deliverables are divided into two parts: A Phase I written report, and a Phase II written report followed by an oral presentation. For the Phase I report, the students, grouped into teams of three or four, propose methods for producing electricity, for which they must provide brief descriptions along with environmental and safety considerations. Each group must also provide block diagrams showing the relationship between the resource and the energy output. The pedagogical role of the block diagram is to force students to contemplate the physical layout of each energy-generation method. For hydroelectric energy, for example, Figure 2 illustrates the relationship between the reservoir, the turbine, and the generator. The groups typically propose one or two methods per team member, and each method requires one to two pages to describe.

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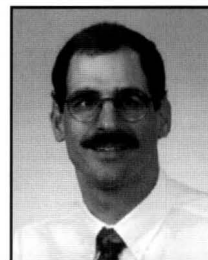


TABLE 1
Press Release for the Open-Ended Estimation Design Project

The island of _____ is a 100-square-mile idyllic spot located _____. Climate, scenery, flora, and fauna all combine to make this a premier vacation spot for families, couples, and those just looking to get away from it all. Abundant recreation activities are available as well as special sightseeing opportunities.

The prime attractions of this island are the miles of scenic beaches with soft, white sand. Breakers pound the shore continuously, making it a year-round haven for surfers. A special locale is the capital port located on the southwest corner of the island. Come spend a languid afternoon visiting this spot and observe the spectacular tidal drop of 40 feet. At low tide, it is a seashell-collector's paradise!

Don't forget the mountains here. Active volcanoes dot the panoramic vistas, and Mount Simone rumbles at least twice a day, spraying a continuous lazy plume of hot gases into the clear blue sky. For the intrepid, guided tours are made to the rim during quieter periods. Come see the most spectacular lava formations on Earth!

Hikers can take trips deep into the heart of the island, where 800-foot waterfalls cascade down into reflecting pools. For those enjoying less strenuous exertions, come spend the afternoon in the hot springs that collect into natural-rock bathing pools. For the conventional individual, we have fresh-water baths; for those looking for something more exotic, we have 2% natural salt baths—guaranteed to improve your skin tone and

leave you feeling healthy. After bathing, come and enjoy a massage at the skilled hands of our staff members. And don't forget, the cleansing effects of a mud bath provide long-lasting therapeutic value to your skin.

Hang gliders will also find plenty of recreational opportunity. The 300-foot lovely cliffs overlooking the ocean afford prime launch locations. The island is renowned for its steady cool breezes that provide year-round hang-gliding opportunities.

And don't worry about bad weather when you come to visit. The sun shines 80% of the time here, with a year-round mean temperature of 85°F and low humidity. Rain, when it occurs, is a late-evening event, so day plans are never ruined.

The island is also abundant with natural resources. Forests of hardwood trees cover over half of the island and contain some of the world's most exotic species of animals and birds. Colorful and extremely rare species of birds can only be found here in the tropical forests.

Spelunkers will also find plenty to do. Mile-long caves provide an opportunity for all levels of cave exploration, from novice to expert. Come down and explore our known caves, or discover new ones of your own! Maybe you will get lucky and find veins of precious metals; large coal deposits have already been discovered.

Don't delay—contact your travel agent now.

The second and main requirement of the Phase I report is including a design equation for each method. The left-hand side of the equation is in terms of energy or power, and the right-hand side is in terms of the fuel or resource and other parameters that will allow for the determination of the amount of energy or power that can be obtained. No calculations are made, however, for the Phase I report, since the resources are not well defined at this point in the project. Rather, the calculations and final recommendation are performed for the Phase II submission.

Separating the development of the design equations in Phase I from the execution of the calculations in Phase II is intentional. Students often find an equation and use it without critical assessment. By delaying the application of the equation from the discovery or derivation, some time will hopefully be spent on critically evaluating the usefulness and correctness of the proposed relationship. The benefit of assessing the design equation becomes apparent to the students when for the Phase II report they have not acquired all the values they need to complete the calculations.

In the case of wind energy, for example, a typical textbook design equation^[3] for the power, P, is

$$P = \eta \rho D^2 v^3 = k D^2 v^3 \quad (1)$$

where v is the wind velocity and D is the blade diameter of the wind turbine. The density of air, ρ , and efficiency, η , are

TABLE 2
Energy Methods Proposed by Students
Hydroelectric
Wind
Geothermal
Hot Lava
Tidal
Ocean Thermal
Fuel Cell
Fossil Fuel
Solar (Photovoltaic)
Hot Springs
Nuclear
Wave
Biomass Conversion
Solar (Thermal)

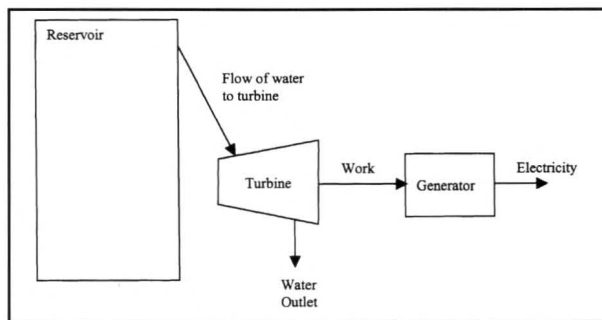


Figure 2. Example of block diagram submitted by a student group for hydroelectric energy.

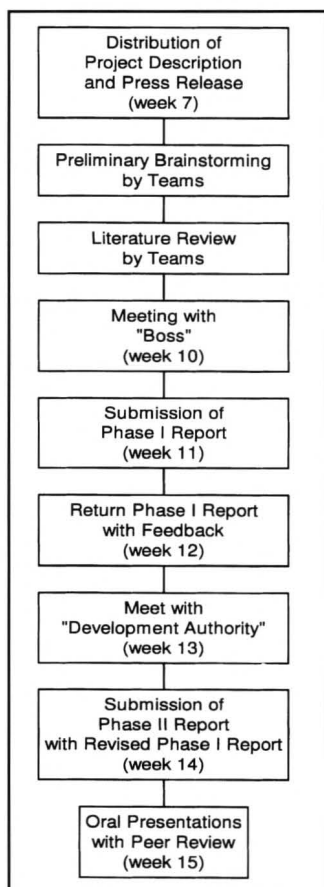


Figure 1. Organization and timeline of the open-ended, estimation design project in thermodynamics.

often lumped into an overall coefficient, k . The correctness of the dependence of the power on the diameter, D^2 , and velocity, v^3 , can quickly be established by observing that the power from wind is related to the rate of kinetic energy change by $\dot{m}\Delta v^2 / 2$ and the mass flow rate, \dot{m} , is equal to $\rho v \pi D^2 / 4$.

The equation for wind energy further illustrates when quantities can be classified as known, easily estimated, or unknown, and thus must be determined by other means. The density of air, for example, can be easily obtained from the ideal gas law, and it is not crucial, for an estimate, if the mean temperature is 65°F or 85°F. The value for the diameter of the windmill, on the other hand, is not necessarily something that can be estimated, but literature sources will typically mention a range of diameters evaluated in actual tests. Finally, it is impossible to estimate the average wind velocity of a location with any certainty; specific values pertain to specific locations.

Wind energy also provides an excellent opportunity to reinforce the usefulness of thermodynamic analysis for calculating energy transformation via the first law. One student, for example, stated that the equation for wind power is not really an outcome of thermodynamic analysis. We then jointly proceeded to evaluate the case of how the kinetic energy change of a gas flowing in a pipe can be related to the shaft work extracted; by extension, wind energy is then linked to the conversion of kinetic energy in the “pipe” swept out by the blades of the wind turbine. Since the wind velocity is also not zero after passing between the blades of the windmill, this point offers partial insight into why the efficiency of wind turbines is low.^[3]

Other methods of generating energy^[3-10] have in their design equations a similarity that is of instructional value for reinforcing the utility of the second law. Burning of fossil fuels, nuclear power, ocean thermal energy, and geothermal energy can all have their design equations represented by the general form

$$P = \eta \dot{m} \Delta H \quad (2)$$

where η is the maximum efficiency, \dot{m} is the mass consumption rate of the fuel, and ΔH is the enthalpy change of the fuel. By casting the design equations in this common format, the maximum efficiency of each method can also be compared on a common basis, namely, the absolute temperature of the hot reservoir, T_h , and cold reservoir, T_c , from the Carnot equation: $\eta = 1 - T_c / T_h$. While some groups choose to use the Carnot efficiency, other teams opt to use an empirical value for η from reference works.

Prior to submission of the Phase I report, the students have an opportunity to schedule a meeting with their “boss,” *i.e.*, the instructor. Since students seem to crave “real world” experience, role playing with their boss provides a good opportunity to get some. Before the meeting, the students are

reminded that their boss does not know the solution to this project. If this were the case, the project would not have been assigned. Furthermore, their boss does not want to solve the problem for them; that is the responsibility of the employee. The boss will, however, guide, encourage, direct, etc.

After submission and acceptance of the Phase I report, the teams “fly” to the island and meet with the director of the local development authority (the instructor), who tries to answer any questions related specifically to the resources of the island. It is at this meeting that location-specific information such as wind velocity, available tidal basin, hydroelectric dam height, and water volumetric flow rate are made available to the students—but only in response to their specific questions. The link between the design equations and known/unknown information then becomes clear. Values for each and every variable in the design equations must be obtained or estimated in order to be able to compute the power. Each group is also given individualized information—no two groups have the same amount of resources or population. In addition, not all of the resources provided are sufficient to meet the energy needs. By tailoring the resources in this manner, groups cannot converge on the same answer and must be comfortable (or uncomfortable) with their own decisions. During the meeting with the local development authority, the values of the resources requested by the students are recorded for later use in grading the reports.

The projects are evaluated for a number of attributes. For the Phase I report, the design equations must be sound and the layouts of the block diagrams logical. Second, the overall organization of the report and writing are assessed. Generally, the Phase I reports have not been graded, but rather feedback for improvement is provided (their boss gives feedback, not grades). The most common shortcoming of the Phase I reports is a poorly formulated design equation. It is either not in terms of a single equation, not in terms of the primary fuel or resource (*e.g.*, for geothermal energy, the power is formulated in terms of the working fluid instead of in terms of the heat available from the hot reservoir), or formulated in a manner for which not all values are easily obtainable.

The format for the Phase II report is a one- or two-page executive summary containing a specific recommendation of how to meet the energy needs of the island. The revised design equations are also presented along with the values used to compute the power. The values of the energy must be roughly correct in light of the fuel or resources specified. Since each group has been given different values for the resources, I calculate the available energy for the methods of each group in a spreadsheet application. In this manner, it is relatively straightforward to determine if each group has correctly calculated the right order of magnitude of energy possible from each proposed method, and it is at this level (namely, the order of magnitude) that the correctness of the calculations is assessed. The revised Phase I report is resub-

mitted as an appendix, and this revision is evaluated for improvements over the original version.

Finally, the soundness of each group's recommendation is strongly weighed. Since at this stage of the design no method of energy generation is strictly right or wrong, as long as sufficient energy to meet the requirements is provided, the recommendation

of each group reflects its evaluation as to what is most acceptable for a resort island and balances what it sees as the competing needs. These are most often a method that is environmentally friendly and aesthetically pleasing. Some groups recommend fossil-fuel power plants as being a tried and true technology, whereas other groups select several methods in combination. The most common recommendation to date has been the use of hydroelectric energy.

The final part of the project is a ten-minute oral presentation by each team for peer review. The three grading criteria are organization of the talk, clarity of presentation, and soundness of the recommendation. The grading process for the oral presentation is conducted in a manner to give students exposure to an assessment practice used in industry. A five-point scale is used, with three as the average, and the students are told that the average of the grades that they award must come close to this average. This is similar to many of the merit raise systems employed in industry where the available "pool" is a fixed percentage of the total salary budget. Use of this method gives the students an opportunity to weigh the consequences of positive and negative assessment and combats any tendency for grade inflation by the teams.

The comments of the students regarding this project were solicited with an anonymous questionnaire, and the results are summarized in Table 3. The most often cited positive aspects of the project were the oral presentations and the open-ended nature of the project. The most negative comments were also related to the oral presentations, two of which can be remedied by better scheduling.

The most frequently cited suggestion by the students pertains to having more specific guidelines for the project. In the experience of the author from seven years in industry, expectations and formats for project presentations and results were limited or non-existent. In general, employees were expected to develop their own presentation formats. The second most frequently cited suggestion pertains to their wish to perform economic estimates. Since this course is offered relatively early in the chemical engineering curriculum, well before their formal design courses with accompanying exposure

TABLE 3
Student Feedback

(Numbers in parentheses indicate the number of times similar types of comments were made in a class of 24 students, 18 of which responded.)

<u>Positive Aspects</u>	<u>Negative Aspects</u>	<u>Suggestions</u>
Oral presentations (7)	Oral presentations on the last day of class (2)	Give more specific guidelines for reports (5)
Open-ended nature (5)	Oral presentations (1)	Require economic estimates (3)
Computationally easy (1)	Problem is too easy (1)	Give more time for project (1)
Opportunity to use people skills (1)		
Role playing (1)		
Research-oriented project (1)		

to engineering economics, this desire to perform economic analyses seems ambitious on their part.

SUMMARY

An open-ended estimation design project has been developed for use in a first thermodynamics course taught early in the chemical engineering curriculum. The project, which contains a number of components

that simulate real-world experience, is designed to emphasize simplification over complexity. A key aspect of the project is decision making; after the values of power for the various methods are calculated, a decision must be made, namely, what ultimately to propose. It is this aspect of the project that is most in line with the expectation of problem solving in industry. The project is also structured to embody many of the elements of critical thinking in that for each team to make a final recommendation, the "students are active, involved, consulting, and arguing with each other..."^[2] Furthermore, several aspects of active learning, such as role playing, writing, and presenting are used to enhance understanding^[1] and retention.^[11] Finally, the project exposes the students to the importance, breadth, and complexity of the numerous issues surrounding the generation of energy.

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