AC 2011-114: CUTTING AWAY FROM THE POWER GRID

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Abstract

One of the course objectives for the junior-level *Thermodynamics* course being taught to our mechanical engineering (ME) majors is "students will analyze engineering systems to evaluate their thermodynamic designs". The Rankine Cycle and its application to power plants were studied intensely. Students were provided with the results of the campus Energy Usage and Emissions Inventory.[1] Some key data which they noted was (1) 74% of the campus energy usage was electricity purchased from the local distributor (2007), (2) roughly 90% of the campus energy usage over the past 10 years was attributed to either purchased electricity or purchased natural gas, and (3) while the student body has grown a modest 8% over the past 10 years, the dollar amount of the energy purchased by Cedarville University has risen 50% over that same 10-year period.

Students were then placed onto teams and assigned one of six alternative energy sources (wind, natural gas, fuel cell, solar, biodiesel, or nuclear) for which they developed a Partial Replacement of Campus Electricity plan. Student teams were required to identify Cedarville's electricity supplier's energy source, its cost of purchasing the electricity, and the carbon output resulting from the electricity purchased by the university. Their task was to locate an existing commercial power generating unit which could generate at least 15% of Cedarville's current electricity demands, compute the capital expenditure to purchase and install the unit, and perform a life-cycle analysis in order to compute total cost to the university over a 30-year period for implementing their plan.

Though Congress has yet to finalize "Cap-and-Trade" legislation, students were also asked to compute the cost savings to the university for a "carbon credit" of $50 per tonne of CO_2 saved. The student teams then developed conclusions as to the viability of their proposals. They freely expressed their feelings about the relative importance of "carbon neutrality" versus their personal educational expenses.

Introduction

The world-wide concern about climate change has led to the designation of carbon dioxide (CO_2) as a pollutant by the Environmental Protection Agency (EPA).[2] Coal is the fuel of choice in the Midwest portion of the United States[3] as well as for the electricity supplier for Cedarville University. Coal also happens to be the fossil fuel which generates the most CO_2 per kWh of electricity produced.[4] Thus, alternative energy sources which reduce the amount of airborne CO_2 are being considered more highly favored for their "green" nature.

The EPA's definition of "green engineering" is "...the design, commercialization, and use of processes and products which are feasible and economical..."[5] By this definition, *cost* becomes a key parameter when engineers turn their talents to alternative energy sources. Thus, the desire to reduce BOTH CO_2 emissions and customer cost became the impetus for the design project whose parameters and results are presented below.

Project Specifications

This paper reports on a power plant design project presented to junior mechanical engineering (ME) majors in their *Thermodynamics* course. The project had a two-fold purpose: (1) the students reviewed the principles of the Single Rankine Reheat Cycle in order to gain a realistic understanding of the overall plant efficiency for one of the best coal-fired plants in the world and (2) the students were required to replace at least 15% of the campus electricity demand with an on-site power-producing unit fueled by an alternative energy source (see Figure 1).

First, the students were told to assume that the Japanese power plant known as the 25 MW Tachibana_wan unit #2[6] was to be operated as a Single Rankine Reheat cycle. Given that the net plant efficiency could be written as the product of three contributing factors:

$$\eta_{net} = \eta_{th} \bullet \eta_{fc} \bullet \eta_{ec} \qquad \text{(EQ 1)}$$

where η_{th} is the cycle thermal efficiency, η_{fc} is the fuel conversion efficiency, and η_{ec} is the electrical conversion efficiency, students were asked to find the two non-computed values on the right-hand-side (RHS) of equation EQ 1 and compute and compare their overall plant efficiency with that presented in the documentation for Tachibana_wan #2.

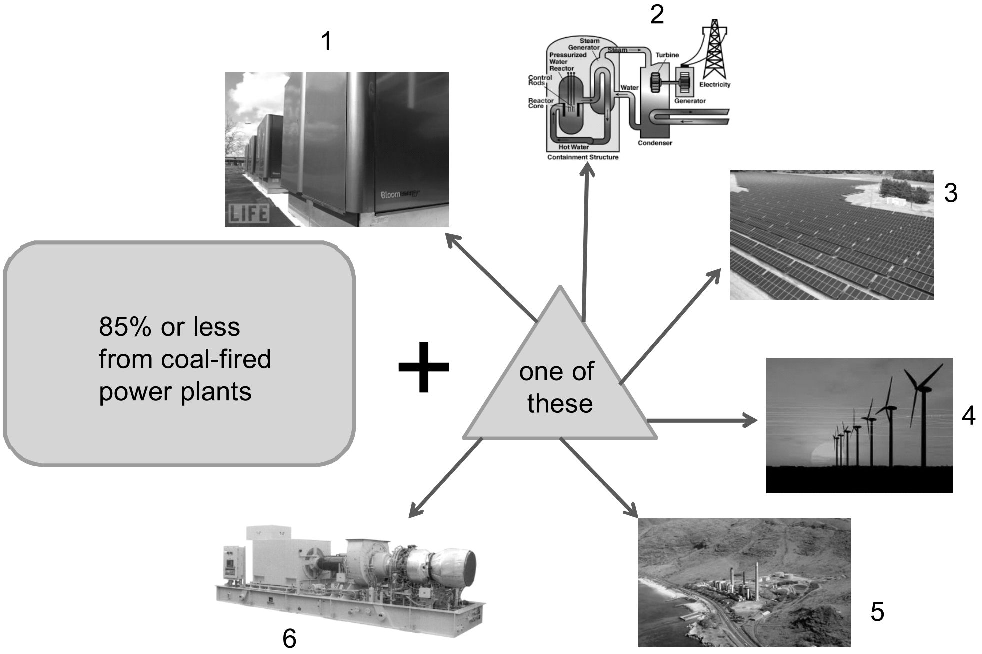

Figure 1. Replacement of at least 15% of Cedarville's electricity from an alternative energy source: (1) fuel cell stack (life.com), (2) nuclear reactor (grid_scitechie.com), (3) solar field (renewableenergy.com), (4) wind turbines (ansys.com), (5) biodiesel (news-bioenergy.com), (6) gas turbine/generator (news.thomasnet.com).

Second, students were given an alternative fuel source. They were asked to locate an existing commercial unit which would be able to supply at least 15% of the campus electricity demand using their alternative source. Students were asked to compute the capital expenditure for purchase and installation of the unit and to amortize the capital cost over a 30-year unit lifetime. The students were also asked to compute the cost savings to the university in two parts: (1) the cost savings of the electricity which would not have to be purchased over the 30-year period and (2) the amount of "carbon tax" which would be saved by having a lower-CO_2 electricity supply. This second sub-component is a reality in the European Union (EU). Though each country has it's own idea of what carbon tax level will be necessary in order to curb CO_2 - related climate change, the current average among EU countries is about $15 per tonne of CO_2 produced.[7] Our students were asked to assume that, once the Congress of the United States finally came to grips with the legislation, a carbon tax of $50 per tonne CO_2 would be necessary to provoke any significant change from the status-quo. Finally, students were to combine their cost savings and balance that against their computed capital expenses amortized over a 30-year life.[8]

Results

Since all student groups analyzed the same existing coal-fired plant, it was interesting to see the diversity of plant efficiencies computed. Though each group started with the same set of thermodynamic information for the cycle, some deemed it necessary to seek out "actual" values for the quality of the steam as it exited the turbines rather than using an acceptable approximation (as suggested by the instructor). Thus, as can be seen in Table I, the computed η_{th} have a broader spread in value than was anticipated.

Table I - Plant Efficiency Calculations

Team	η_{net}	η_{th}	η_{fc}	η_{ec}
Wind	35.7%	38%	95%	99%
Solar	32.0%	34%	95%	99%
Biodiesel	32.0%	34%	95%	99%
Natural Gas	27.1%	30%	95%	95%
Fuel Cell	32.3%	35%	95%	97%
Nuclear	36.1%	40%	95%	95%
Coal (Baseline)	43.5%	---	---	---

It was the second major component of this project which provided the most fascinating results from the student groups. Since each was constrained to locate an existing power generation system, the uniqueness of the alternative energy source provided a vast range of both capital expenditures as well as 30-year lifetime savings (expenses) for the university. Additionally, each group quoted both a unique kWh electricity cost from the current campus supplier as well as a unique CO_2 production amount from burning coal. The 30-yr cost savings (expenses) per kW required was computed for each alternative fuel. Table II shows these results.

Table II - Energy Cost Analysis

Team	kW	Capital Costs	E-Savings (30-yr)	C-Savings (30-yr)	Total Savings/kW (30-yr)
Wind	671	$5.7 M	$17.4 M	$8.7 M	$0.030
Solar	625	$40 M	$16.34 M	$7.6 M	($0.026)
Biodiesel	625	$0.5 M	$0.0 M*	$2.8 M	$0.004
Natural Gas	625	$4.1 M	$0.3 M**	$3.25 M	($0.001)
Fuel Cell	700	$5.25 M	$8.44 M**	$4.83 M	$0.011
Nuclear	15,000	$70 M	$469 M***	$54.85 M	$0.030

*   Requires the purchase of alternative energy supply in the form of biodiesel
* *   Requires the purchase of alternative energy supply in the form of natural gas
* * *Assumes the extra electricity generated is sold back to the power grid

Discussion

The first objective for the project was to have students recognize how theory and practice interface. Since their computation of the thermal efficiency for the Tachibana_wan power plant was constrained by their assumption of a Single Rankine Reheat cycle, they were clearly not going to achieve the stated overall plant efficiency of almost 44%. One group stated the obvious:

> Since our η_{th} came out to less than the given overall plant efficiency, and since each of the other efficiencies has to be less than unity, we clearly have made a gross assumption here.

Though the class was not specifically directed to determine how many regenerative components (i.e. feedwater heaters) were incorporated into the Tachibana_wan plant, they knew enough about them to recognize their contribution to improved cycle efficiencies.

The second objective for the project illumined many of the students to the issues which comprise current climate change and energy policy. They have been introduced to the Nobel Prize-winning documentary *An Inconvenient Truth.*[9] They have been made aware of the controversy over anthropogenic CO_2 from the burning of fossil fuels.[10, 11] The impact upon the students as citizens can not be understated. Having cranked the numbers for this class project, students were able to pull the engineering truths from among the political and media hype. The students understood that, independent of whether or not CO_2 in any way affects the climate, certain fuels produce certain amounts of CO_2. Their research brought them face-to-face with the amount of CO_2 delivered to the atmosphere by coal-fired plants as well as the costs which are incurred by having to mitigate against such CO_2 outputs. The following quotes express their enlightenment:

> The lack of CO_2 emission for wind power is a major factor in contributing to the cost savings. This clean source of power is very efficient and cost effective once it is paid for and installed. (Wind Team)
>
> Though replacing 15% of our electrical energy by building a natural gas turbine generator facility would not be cost effective, this idea is not without merit. Reducing the emissions of CO_2 would create a near-even exchange of costs and, hence, be worth it in the long run. (Natural Gas Team)
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> We realize that there will be additional expenses incurred in the production and sale of electricity, however, the numbers demonstrate that this alternative source of energy could be extremely profitable for the university as well as significantly cut CO_2 emissions. (Nuclear Team)
>
> Even if the penalty were \$50 for every tonne of CO_2 produced and neglecting the maintenance costs over the life of the installation, it would still take over 60 years for the solar power plant to begin saving the school money. (Solar Team)
>
> Over the 30 years, a conversion of 15% of the university's electricity to come from biodiesel would save us only the carbon tax credits which have yet to be determined by our political leaders. (Biodiesel Team)
>
> The installation of seven Bloom Energy ES-5000 (100 kW) units requiring natural gas would save the university over eight million dollars over a 30-year period and reduce CO_2 emissions by 60% for the replaced portion of the electricity. (Fuel Cell Team)

Conclusion

We have chosen to integrate energy production and policy into a project through which students are encouraged to become more active as citizens. Some groups of students expressed joy that the implementation of their alternative source of electricity could reduce costs for future students. Other groups made the connection between the use of alternative energy sources and CO_2 reduction. Our hope is that future generations of MEs will be more globally aware than their predecessors. Wouldn't it be wonderful if clear-thinking, problem-solving, unbiased MEs would become involved in developing our nation's energy policy?

References

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