Undergraduate Design Project Ideas in Sustainability: Rethinking Ammonia Synthesis

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Chemical Engineering Product Designs for Sustainability-Rethinking Ammonia Synthesis for Sustainable Distributed Production Systems

Abstract

We are piloting undergraduate product design projects that address a chemical process very familiar to students - ammonia synthesis - and that use process simulation tools that they are comfortable with (after process design), but that have design objectives that are unusual and new to the students. These new objectives are those governing sustainable, distributed, carbon-free small-scale ammonia synthesis systems. Such systems are called for in unusual circumstances where stranded renewable energy resources (wind, solar, etc.) need to be used, and ammonia can provide energy storage, hydrogen-carrier, and fertilizer possibilities. In our case we can also offer the students the opportunity to use data from a working pilot plant (associated with a wind farm). The poster presentation will describe our experience with the teams of student piloting this product design, focusing on pedagogical challenges and progress that will be of interest to other ChE design instructors.

Introduction

This poster will present lessons learned, practices recommended, and objectives achieved when assigning a new pilot team project in our Senior ChE Product Design course. The features of this particular pilot project that may be of interest to the ChE education community include:

- the use of process design skills (acquired by students in the preceding ChE Process Design course), now put toward a product design effort
- a sustainability focus, where the product is a system that allows small-scale, distributed - possibly even portable - ammonia production systems to capture stranded zero-carbon renewable energy (e.g., wind, solar, etc.) [1]
- the use of the product design approach and stage-gate decisions (where the process being designed would be the "product" under consideration) [2]
- the ability to draw some design data from the operation of a working pilot plant associated with a wind turbine for zero-carbon-footprint fertilizer [3]
- exposure to research efforts on chemistry that is very different from traditional Haber-Bosch catalysis that might be used in the future in these unusual circumstances.[4-6]

In assigning this type of project, we are afforded the opportunity assess the teaching and coaching of skills that stretch the traditional ChE curriculum, including design for distributed manufacture and sustainability, design under scenarios where traditional economic potential and net present value are difficult to calculate and depend on many policy, economic, geographic, and political scenarios.

Course outcomes that will be assessed particularly with the use of this pilot project:

1. Experience in teamwork that uses multidisciplinary information but emphasizes the role of the chemical engineer; helping prepare for participation as chemical engineers in industrial multidisciplinary project teams.
2. Experience in product/process design decisions (e.g., stage-gate decisions) such as those currently practiced in chemical product industries.
3. Discover and use data and background information needed for the design from patent, technical, trade, and specialty-application literature
4. Exposure to contemporary issues in chemical engineering
5. Awareness of intellectual property issues.

Examples of initial project descriptions provided to all students to enable project selection:

1. Distributed zero-carbon-footprint mini-Haber-Bosch ammonia synthesis facilities[7-10]

We would like to explore what influences the "optimum" design at various scales and with various cost structures (including policy, incentive, mission) of a zero-carbon mini-Haber-Bosch ammonia synthesis plant that takes advantage of "stranded" renewable energy. Such a pilot plant now exists in the university; it uses only energy from wind, hydrogen from electrolyzed water, and nitrogen from membrane or adsorbent separated air; it is being studied by university researchers for zero-carbon agriculture, and visits from the team are welcome. The product for this team is not the ammonia; rather it is the mini-plant that could be installed at remote locations to create fertilizer (our current focus), or to create ammonia for other purposes (e.g., a liquid hydrogen carrier for hydrogen fuel cells.

2. High temperature absorption units for a low-capital ammonia capture in distributed zero-carbon-footprint mini-Haber-Bosch ammonia synthesis facilities [11-14]

One of the major limitations of small-scale ammonia synthesis (taking advantage of stranded renewable energy) is the need for high pressure and for condensation separation - both make the capital cost very burdensome. We would like the team to design a solid absorber (using solid-state ammine chemistry) that could be used to replace the current condenser in a small-scale Haber-Bosch plant. The product being considered by this team is not the ammonia; rather, it is the absorber system that might be used as a replacement for conventional condenser in such plants in the future.

Excerpt from an example detailed project description provided to a team:

Conventional ammonia synthesis is a very energy-intensive and capital-intensive process, so it is typically designed a very large scale. High temperature and pressure are the prerequisites of the reaction to achieve respectable rates and conversions. According to the USDA, a huge amount of ammonia is produced (13 million metric tons per year) in the U.S.; it is one of the largest volume commodity chemicals, and 80% of US ammonia is consumed in the agriculture sector.

Still, there is incentive to learn how to design smaller and less capital-intensive plants. Even in the US and Canada, when a power available from a wind farm in the Great Plains exceeds the grid capability to take the power, there is a need to store or otherwise usefully use the power. During times of high agricultural ammonia demand (in seasons for fertilizing), it is attractive to use that power to make ammonia from air (for nitrogen) and water (for hydrogen). An attractive feature of this ammonia is that it does not need natural gas for the hydrogen, so it does not cause CO_2. The economic driving forces for design, though, are unusual. The plant should be appropriately sized (perhaps quite small), located near the stranded power source, and able to use the excess power when it is available; its size, weight, and capital cost must meet unusual requirements; and its financing will also probably be different than for a conventional plant, perhaps responding sensitively to external trends (e.g., carbon emission penalties by government, or green initiative incentive by companies).

Moreover, small-scale production processes can serve critical needs in remote locations (e.g., near farms in underdeveloped nations with limited fertilizer distribution; or in remote installations or teams (research, rescue, or military) with limited access to liquid fuel). In such cases, this process would not be in direct competition with commercial ammonia production, and the energy would be obtained from a renewable resources (such as wind or solar). Although capital costs might be covered by an external funder (government, grant, etc.) we would like to make sure to design a process that is efficient and meet the needs of customers that we target. So here is an overlook of what you should follow in your process design:

- Identify your target customer/user, whose needs you would like to serve (an explorer in Antarctica, a village farm coop in Africa, a remote military or research installation, an island with few petrochemical resources,...others?).
- Assess their needs. (For instance, what quantity and quality of ammonia production? When needed? Expertise available to operate?)
- What is your production target? What is the target scale/size/weight? (Hand-pulled or animal-pulled cart, car trunk, tractor, etc.)
- Who is going to be the end-user? What expertise you expect they have? Consider different degrees of complexity! A farmer? An explorer? A trained research technician?
- What balance do you envision about uses of ammonia: e.g., as fuel, as fertilizer, as a hydrogen source for H_2 fuel cells, etc?
- What mode(s) of production should you consider? (batch, continuous, other?)
- What might affect the optimum pressure and temperature for the production facility, considering the limitations by the resources or expertise of the operator. Should you consider process conditions very different from typical commercial-scale conditions (e.g., T and P)? What tradeoffs are there (e.g., in capital vs. energy intensity)?

- What effect might you anticipate from governmental regulations or from public pressure? Consider what new environmental policies might be set. What are those probable policies? Carbon tax? If that's the case, how does it impact the economics of your process and how would it affect your design decisions?
- How might you reduce the capital cost and complexity? How might you reduce the operating cost and improve efficiency of making ammonia per unit of energy used? Can you project trends in these over relevant scales of production?

Preliminary assessment of outcomes

The following course outcomes are at a preliminary level of assessment from this pilot effort:

1. Experience in teamwork that uses multidisciplinary information but emphasizes the role of the chemical engineer; helping prepare for participation as chemical engineers in industrial multidisciplinary project teams.
    a. Three teams (each with three or four team members) attempted this type of project. The team work started with conversations with researchers who could relate the environmental and sustainability imperative, history of work done to date (including construction and testing of the pilot plant), and review of literature (multidisciplinary in nature). Two researchers acted as "clients", providing a charge to each team with a request for design recommendations. The charge memo provided a very open-ended design task (this is the second design course; the first is a much more traditional chemical engineering process design experience).
    b. Each team needed to work on a tight schedule to produce recommendations for the "client". While chemical engineering issues were the primary focus of the team's work, the context of the design challenge required understanding of multidisciplinary issues - each team found particular difficulties in doing this, but the experience is viewed (both by instructors and students) as beneficial for the students' early career.
    c. The "client" for the project was represented by the multidisciplinary research team (including views from an agricultural economist, a systems engineer, the director of a renewable energy outreach effort for farming coops, and a policy analyst). Such multidisciplinary input from the "clients" tended to inhibit the student teams' independent search for multidisciplinary information on their own, but it tended to sharpen their action and self-perception as chemical engineers who could focus on chemical engineering aspects of the large questions.
2. Experience in product/process design decisions (e.g., stage-gate decisions) such as those currently practiced in chemical product industries.
    a. The first tasks were clarification of the *context* of the design challenge, and of *needs* of the "client".
    b. Generation of *ideas* to meet the chief needs of the client took most of the time available. This involves mastery of literature and concepts new to the students.

    c. *Selection* from among the leading ideas, and formulation of recommendations related to possible *manufacture* and to potential *risks* and engineering standards.
    d. Guidance from the "clients" tended to de-emphasize conceptual brainstorming, but it also tended to sharpen the critical thinking devoted to possible solutions to problems. With the limited time and resources of this course, the instruction team facilitated exploration of specific case studies rather than broad decision matrix analysis.
3. Discover and use data and background information needed for the design from patent, technical, trade, and specialty-application literature
    a. Independent discovery by the student teams somewhat less than typical - more guided by discussion with the "clients" for these projects.
    b. A compromise that is probably worthwhile so that the students have the chance to experience more interaction with an actual research project.
4. Exposure to contemporary issues in chemical engineering
    a. Unusual design constraints and deliverables
    b. Multiple realistic constraints and some form of engineering standards that are presented from a sustainability and life-cycle-analysis perspective
5. Awareness of intellectual property issues.
    a. Less clear for this project than for typical "product design" projects.
    b. A compromise that is probably worthwhile so that the students have the chance to experience more interaction with an actual research project.
    c. Awareness of potential intellectual property issues can tend to inhibit, rather than promote, open discussion between the client and the student team. In the future this dynamic needs to be anticipated and thought through in a fashion similar to engineering design projects that are "sponsored" by a company.

Conclusion

A major "win" for the individual students participating in these teams, and also for the entire class experiencing the progress of these teams in regular presentations, was a strong growth of interest in projects that involve agriculture, the food/energy nexus, life cycle analysis, net carbon impact, and the concept of distributed production to use stranded renewable carbon-free energy.

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