Integrating sustainability into Chemical & Biological Engineering curricula at UBC

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Introduction

Sustainable development means industrial progress that meets the needs of the present without compromising the ability of future generations to meet their own needs. The current practice of society and the world is obviously unsustainable, reflected by those major issues on population growth, energy consumption, global climate change and resource depletion. Sustainability has four basic aspects: the environment, technology, economy, and societal organization. Conventionally, engineers are taught to deal with technology development and economic analysis to assess the economic viability of a process, a product or a project. They are not familiar with the optimization of the human benefit from the technology development and the environment where materials and energy are available. In the past 20 years, there has been a rapid evolution of academic and industrial approaches for integrating environmental and social considerations into process and product development and business decision-making toward sustainable development, with many inter-disciplines or fields proposed across different scales. As one of leading teaching and research institutions in Canada, UBC has been pursuing the sustainability vigorously on research, teaching and services. In the department of Chemical and Biological Engineering, we have been taking initiatives in introducing pollution prevention, green engineering and sustainability into our curricula since 1996. This presentation will cover the experience of the sustainability program in the department, and the future planning for incorporating sustainability into the Chemical and Biological Engineering Curricula.

Evolution from pollution control to pollution prevention, green engineering and sustainability

To shift our conventional teaching of pollution control to pollution prevention, which includes both source reduction and recycling, into the curriculum of the Chemical and Biological Engineering program at the University of British Columbia, we introduced a 4th year elective course on pollution prevention engineering (CHBE484) in 1996, with focus on source reduction and process recycling for chemical processes. The book “Pollution prevention for chemical processes” by David Allen and Kirsten Rosselot was used as the textbook, with emphasis on pollution prevention for unit operations of chemical processes. The topics covered are:

- Waste audit and inventories of chemical processes;
- Methodology for implementation of waste minimization programs;
- Impact of in-process changes on waste production;
- Development of closed cycle technologies.
- General concept of mass and energy exchange and industrial ecology;

This course supplemented our traditional environmental engineering courses such as Water Pollution Control (CHBE373), Air Pollution Control (CHBE485) and Hazardous Solids Waste Processing (CHBE480), and gaining increasing interest from students with enrollment increased from 6 in the first year to 30 by 2000.

To address the sustainability at a larger scale, the CHBE484 course was revamped to a Green Engineering course by introducing topics on sustainability, life cycle analysis, environmental systems analysis, green engineering and industrial ecology, going beyond the boundaries of traditional chemical processes. Meanwhile, the pollution prevention concepts have been gradually integrated into other pollution control courses. For example, the Air Pollution Control course now covers not only control components but also prevention and greenhouse gas emission reduction components. Topics currently covered in the green engineering course are:

- Introduction to pollution prevention, cleaner production, green chemistry and engineering, industrial ecology and sustainable development;
- Waste audit and inventory, and pollution prevention options for unit operations;
- Environmental impact assessments: LCA assessment, total cost analysis and environmental systems analysis;
- Eco-industrial parks: material and energy exchange and integration, reduce/recycle/reuse of wastes and by-products.

Approaches, philosophies and case studies of the course.

Sustainability or sustainable development has a broad essence, involving multi-disciplinary approaches at multiple scales. As shown in Table 1, there have been many research areas and terminologies relevant to sustainable development. To introduce our students to such a complex topic, we felt that it is essential to provide a systematic prospective view on various terms ranging from green chemistry, pollution prevention to industrial ecology so that a clear relationship among those terms across multi-scale and multi-disciplinary can be established for the students. We tried to group all terms according their scales of research subjects, with some terms located across two scales as shown in Table 1. The relationship between different scales is established in Figure 1 using terms representative at each scale, i.e. green chemistry at microscale, green engineering at the meso-scale, industrial ecology at the macro-scale and sustainable development at the global scale.

Table 1. Lists of some synonyms, disciplines or fields related to pollution management and sustainable development at various scales.

Micro-scale	Meso-scale	Macro-scale
➢ Green chemistry ➢ Environmentally benign chemistry	➢ Pollution prevention ➢ Cleaner production ➢ Green engineering ➢ Green chemical engineering ➢ Green process engineering ➢ Green design ➢ Clean technology ➢ Environmentally conscious process engineering ➢ Ecologically conscious process system engineering ➢ Ecological process engineering ➢ Ecologically considerate chemical engineering ➢ Ecological engineering ➢ Engineering ecology ➢ Natural engineering ➢ Sustainable engineering	➢ Industrial ecology ➢ Industrial metabolism ➢ Eco-industrial park ➢ Eco-industrial complex ➢ Eco-industrial community ➢ Eco-industrial network ➢ Eco-industrial development ➢ Sustainable community ➢ Sustainable agro-ecology ➢ Eco-technology ➢ Earth systems engineering ➢ Ecological engineering ➢ Engineering ecology ➢ Natural engineering

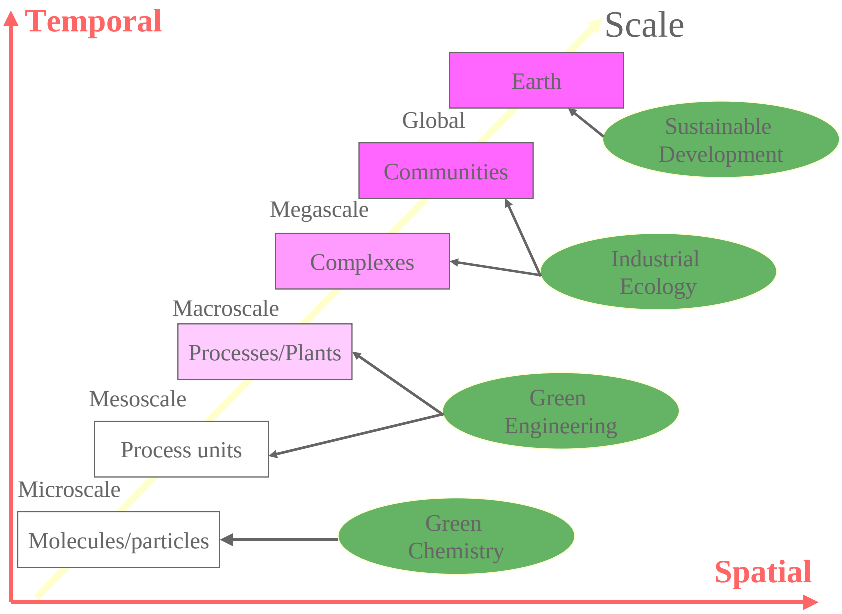


Figure 1. Integrated multiscale approaches toward sustainable development.

The relationship among pollution prevention, cleaner production and green engineering at the meso-scale, which is most relevant to the industrial processes chemical engineers work for, is further clarified in Figure 2. Both pollution prevention and cleaner production put emphases on material and product manufacturing while the green engineering goes beyond to include the whole life cycle of the product, with more emphasis on the impact of the product over its whole life cycle.

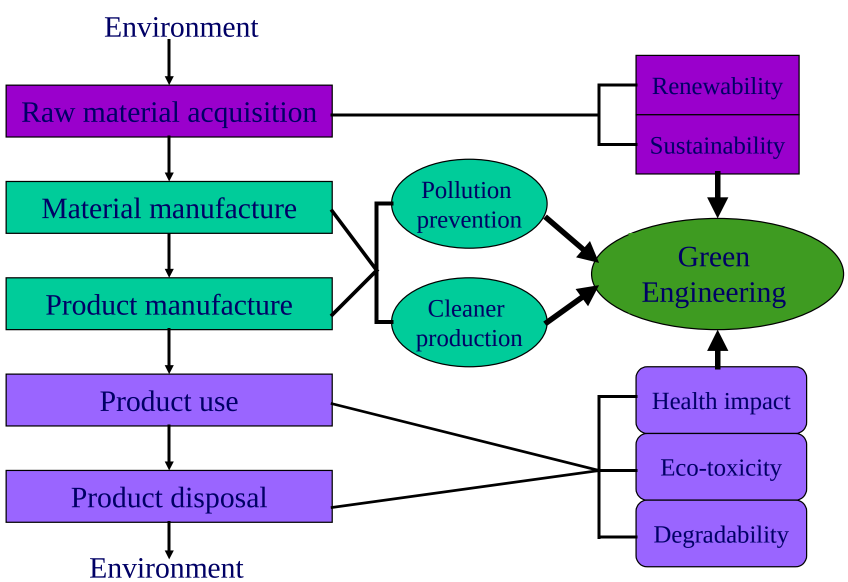


Figure 2. Relationship between pollution prevention, cleaner production and green engineering.

To visualize how researches at different scales can be linked to contribute to the sustainable development by engaging chemists, chemical engineers and systems engineers, we introduced the clean technology and eco-industrial park in Figure 3. Clean technologies are those developed following the principles of green chemistry and engineering at the micro and meso scales through chemical synthesis and unit operation and process development. The eco-industrial park, on the other hand, is achieved by promoting energy and waste material exchanges in a complex adopting clean technologies and following the industrial ecology principles.

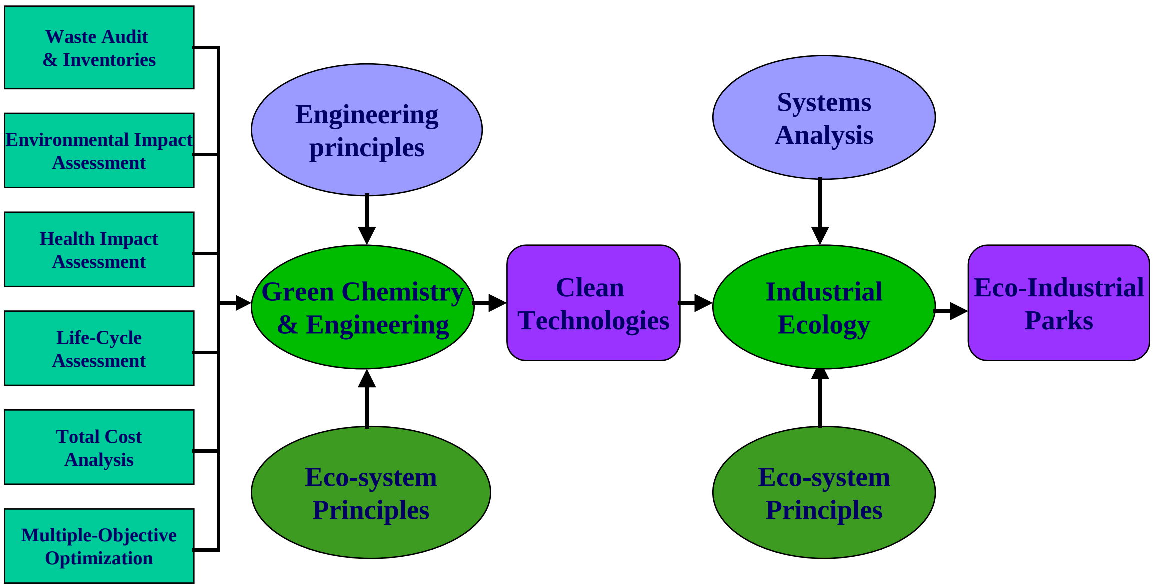
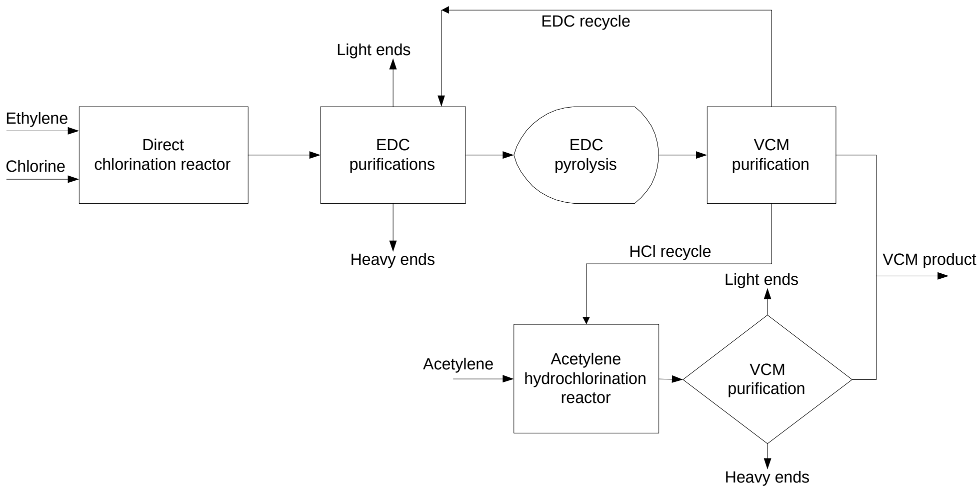
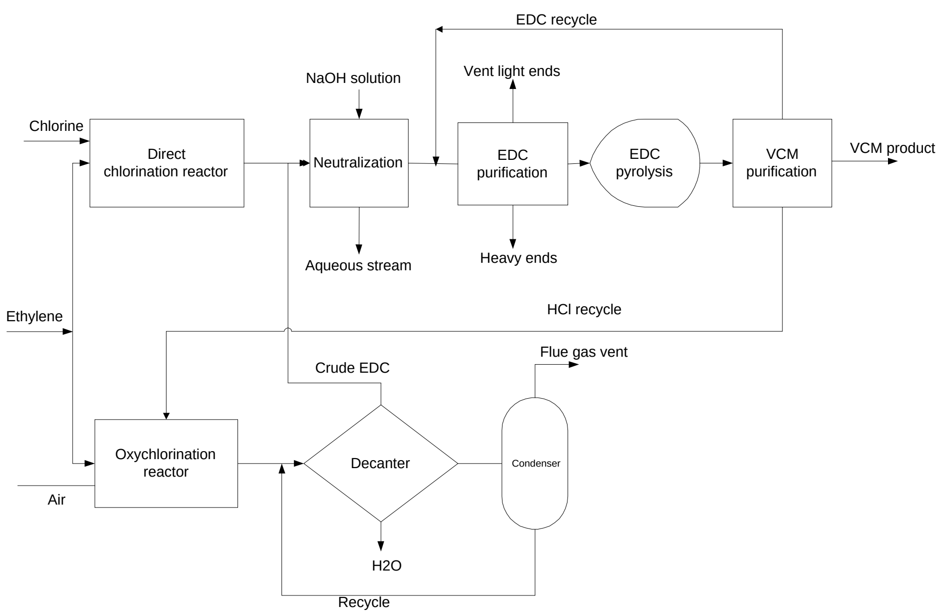


Figure 3. Tools, principles and pathways leading to clean technologies and eco-industrial parks.

Since its inception, two unique features of the Pollution Prevention and Green Engineering course at UBC have been developed. One is invited lectures on industrial practices of green engineering, ranging from life cycle analysis of clean and renewable energy to eco-industrial parks/networks, and the other is the extensive use of case studies. The former provided students with the industrial prospects on applying green engineering principles and the latter taught students on how to piece together approaches to analyze a chemical process or a plant. We found that the VCM (vinyl chloride monomer) production process is an excellent example to illustrate how to implement pollution prevention strategies in industrial chemical processes. Starting from the reaction pathway synthesis, the selection of ethylene over acetylene perfectly illustrated the importance of raw materials selection on pollution prevention. Then the combined direct ethylene chlorination and acetylene hydrochlorination process (Figure 4a) in which hydrogen chloride is recycled to an acetylene reactor, and balanced VCM process (Figure 4b) in which the hydrogen chloride by-product from direct chlorination is recycled to the oxychlorination reactor demonstrated the in-process and on-site recycle principles perfectly. The use of fluidized bed reactor over the fixed bed reactor for oxychlorination and the use of liquid-boiling reactor which combines the reaction and distillation in a single slurry reactor showed how the development of novel and compact unit operation can help for waste minimization. The modification of unit operations for preventing gas pollution is discussed by considering the replacement of air by oxygen for the oxychlorination reactor. Based on simple mass balance analysis, students learned that the reduction in flue gas flow rate due to the elimination of nitrogen could lead to more than 90% reduction of VOC emissions from the oxychlorination process. Application of the same technique for other oxidation processes such as natural gas partial oxidation and chemical looping combustion is also discussed in the class.



(a)



(b)

Figure 4. Schematic of (a) the combined direct ethylene chlorination and acetylene hydrochlorination process and (b) the balanced direct chlorination and oxychlorination process.

Another use of this case study is to make an easy transition of the course from process pollution prevention to industrial ecology and life cycle analysis. By expanding the boundary beyond the VCM process to include the processes for chlorine and ethylene production, as well as the production of PVC from VCM, it demonstrated how one can apply streamlined life cycle analysis or environmental systems analysis to examine a chemical process to identify pollution prevention opportunities. Furthermore the concepts of environmental systems analysis and the industrial ecology are well demonstrated by expanding the process boundary to include the mass and energy integration in the PVC plant.

The second case study used in this course is the life cycle comparison of alternative-fuel powered vehicles in which the life cycle analysis of commercially available gasoline cars, electric cars and PEM fuel cell cars are used to demonstrate the LCA principles and applications. The life-cycle stages of fuels/energies for electrical, hydrogen fuel cell and gasoline ICE (internal combustion engine) vehicles are broken into three sub-cycles, i.e. fuel cycle, vehicle cycle and powertrain cycle, see Figure 5. By doing so, the LCA comparison can be focused on the fuel cycle and powertrain cycle only by assuming that different engines/powertrains are installed into the same vehicle. By further assuming that the same power specification from the three power sources is used in all the three types of vehicles for comparison, a consistent functional unit is warranted in the analysis.

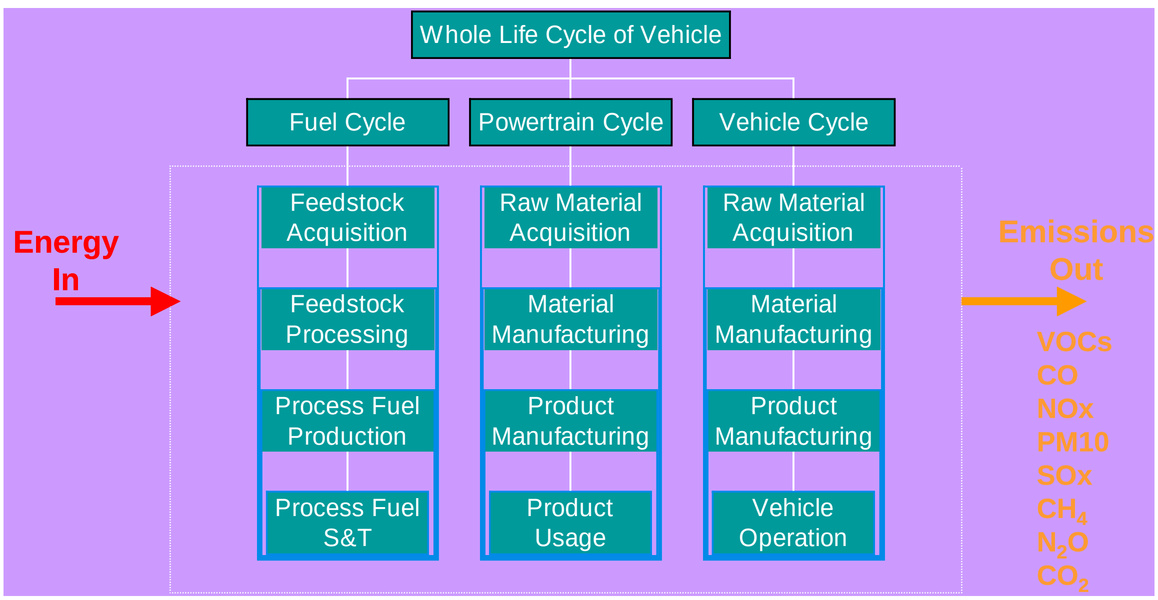


Figure 5. Life cycles of internal combustion engine gasoline vehicles, electric vehicles and fuel cell vehicles.

Rather than starting from the scratch, this case study used inventory data reported in the open literature on fuel production [e.g. gasoline from crude oil, electricity from hydropower (90%) and natural gas power plant (10%) based on British Columbia power mix, and hydrogen from natural gas steam reforming], fuel cell stack production, battery production and ICE engine production to build the total emission inventory. The final emission inventories for 4 commercially available vehicles are given in Table 2. It is seen that the electric vehicle (RAV4-EV) releases more or less the same amount of CO_2 over the whole life cycle compared to the ICEV (RAV4). Similarly currently available fuel cell vehicles (Honda FCV) contribute to only a fractional reduction in CO_2 emissions compared to the ICEVs (Honda Civic HX). However, both electric vehicles and fuel cell vehicles reduced the emission of other air pollutants significantly, especially for fuel cell vehicles, because of the centralized emission control system for power plants and hydrogen plants, compared to the emission from individual tailpipes. In combination of the emissions from rural areas where most power plants and centralized hydrogen plants are located, both electric vehicles and fuel cell vehicles are expected to result in significant reduction in human health impacts.

Table 2. Comparison of gasoline ICE vehicles, electric vehicles and fuel cell vehicles.

	ICEV	EV	FCV	ICEV
	TOYOTA RAV4-2002	TOYOTA RAV4-EV-2003	HONDA FCV-2003 (Ballard)	HONDA CIVIC HX-2002
Pollutants	g/km	g/km	g/km	g/km
CO_2	261	299	176	196
CH_4		1.09	0.85	
N_2O		0.002	0.004	
CO	6.11	0.18	0.10	5.5
SOx	1.58	1.01	0.23	1.06
NOx	1.39	0.79	0.27	1.06
NMHC	0.65	0.29	0.23	0.47
PM	0.11	0.01	0.05	0.07

Such a simple but realistic case study not only trains students how to conduct a proper life cycle analysis by selecting the right functional groups, but also makes students to think about how to use their knowledge to clarify debates and perceptions in their real life. Furthermore, the same case study can be expanded to cover the industrial ecology by looking into the possible options for the utilization of excess steam from hydrogen filling station with on-site hydrogen production by forming a heat exchange network.

Term projects and term papers

The second feature of the green engineering course at UBC is the term project/paper. Students were required to undertake a term project or to write a term paper, preferably in a group of 3 students, with the subject covering broad areas of pollution prevention and sustainability. Three types of projects can be considered by the students. Type one is to propose a green engineering project, including the outline of the problem, the approach to be adopted, and the significance of the work. This type of projects is especially suitable for the co-op students who have worked in industries during their co-op terms and are familiar with some specific processes. Over years, various industrial processes have been covered by this type of term paper, with a few representative ones given in Table 3. Most students were able to apply the principles learned from this course to the industrial processes they worked on before to identify potential pollution prevention options. Techniques used in these term papers ranged from waste audit and emission inventories, pollution prevention options for unit operations such as raw material substitution, in-process recycling, unit modifications and new technologies, to total cost analysis and energy exchange for local industrial parks.

Table 3. A list of some representative term papers related to students' working experience.

	Title	Subject
1	Chlorine substitution in the pulp bleaching sequence	Source reduction by feed substitution in pulp bleaching process
2	Emission inventory in Lafarge Cement Plant	A waste audit and inventory of air emissions based on the student's co-op work in Lafarge Cement Plant
3	Reducing fuel consumption in the Lloydminster Refinery	Proposed several ways for energy conservation based on the student's co-op work for a refinery
4	Reduction of sulfur dioxide emissions at cominco's trail smelter	Pollution prevention for zinc sulfide roasting operation based on the student's co-op work in Cominco
5	Pollution prevention: a co-op student's perspective	Process analysis of the student's co-op work for P2 opportunities
6	Pollution prevention techniques used at an EDC distribution centre	Fugitive emission control based on student's co-op work
7	Pollution prevention analysis on Burnaby incinerator	A team work based on their 4th year design project on the revamp of a local municipal waste incinnerator
8	Proposal to replace traditional energy sources with wind energy at the Vancouver International Airport	A review and feasibility study on the airport based on the student's co-op experience
9	An investigation of anaerobic digestion as a treatment option for dairy farm wastes	A review and analysis based on the student's work in a family owned diary farm
10	Crude oil storage tank emissions and their controls	Emission audit and inventory analysis based on the student's co-op work in an oil distribution company

The second type of projects is to carry out a small green engineering project for a community, a process or a specific unit operation or product. Students are allowed to form a team of 3 people. Over years, students have been working on various hand-on projects related to regional energy issues such as energy exchange network for municipal waste incinerators, life cycle analysis of fuel cell vehicles, energy efficiency in local green houses, and specific issues such as the storm water management, waste solvent recycling, selection of campus utility gator vehicles based on overall impact assessment, used chemical exchange programs, with all related to the campus sustainability initiatives. To identify potential projects related to the sustainability across the campus and the region, we have closely collaborated with the University Sustainability Office and the Department of Health, Safety and Environment. Working side by side with sustainability and environmental officers at UBC, students learned more on how to apply what they learned from the class to serve the community. Some of the representative projects are listed in Table 4.

Table 4. A list of some representative term projects related to local communities.

	Title	Subject
1	Pollution prevention in campus	An audit and inventory of the traffic situation in UBC campus
2	Pollution prevention strategies implemented to the UBC's heating system	An audit and inventory of the heating system in UBC buildings and proposed possible energy saving options
3	Recycling systems in Gage Residence	An audit and inventory of the recycling system and possible areas of improvement in one campus residence building and possible P2 options
4	A pollution prevention evaluation of the UBC composting project	Process analysis to identify P2 opportunities for the UBC campus waste composting project
5	Pollution prevention by integrating urban development with the environment using UBC campus as an example	An exploration and proposal for campus pollution prevention strategies
6	Development and evaluation of alternative	An audit and inventory of existing campus solvent

	waste solvent streams	recycle program and P2 options for the future recycling program for UBC Sustainability Office and Environmental Office
7	Testing and analysis of UBC water discharge sites during non-storm events	An audit and inventory of the storm water quality and emissions for UBC Sustainability Office and Environmental Office
8	Waste audit of Chemical Engineering Building	An audit and inventory work for UBC Sustainability Office and Environmental Office
9	An investigation into a P2 project on greenhouse gas emission control in British Columbia	A review on existing greenhouse emission and environmental and economic benefits
10	Pollution prevention for a small unit in society	An audit and inventory of a fast food counter at Richmond Centre, a local shopping mall, and P2 opportunities
11	Anaerobic farm waste digestion for rural BC farms	A case study of a local diary farm based on the comparison of uncontrolled emissions with emissions from an anaerobically treated wastes
12	Proposal to replace traditional energy sources with wind energy at the Vancouver International Airport	A review and feasibility study on cost
13	Sustainability analysis and recommendations for Black Tusk Village	A analysis of a small community at BC on its waste reduction and management
14	Biodiesel: comparison of an alternative diesel fuel	An analysis of emissions and environmental impact for locally produced biodiesel
15	Is hydrogen fuel cell currently sustainable?	A Life cycle analysis of Fuel Cell vehicles based on literature data

The third type of projects is to critically review a successful pollution prevention or green engineering project, including its approaches, techniques adopted and analysis. The students are encouraged to identify shortcomings and then to propose possible improvements to the project based on green engineering principles, or to propose how to conduct a similar approach locally. Some of the representative examples are given in Table 5. This type of term papers is most suitable for the non co-op students who have not had exposure to a specific industrial process but would like to familiarize themselves with certain industrial process in order to identify areas for improvement in pollution prevention.

Table 5. A list of some representative review type term papers.

	Title	**Subject**
1	Chlorine substitution in the pulp bleaching sequence	Source reduction by feed substitution in pulp bleaching process
2	Westport Innovations Inc. Clean technology/transportation	A description of a local company, Westport's natural gas substitution for the diesel engine
3	Examination of two studies in industrial ecology	Utilization of gypsum from flue gas desulfurization in two power plants are reviewed and discussed
4	Pollution prevention in the pulp and paper industry: life cycle assessment application	A discussion of the life cycle analysis for pollution prevention in the pulp and paper industry
5	Pollution prevention - Aircare program in British Columbia	A review of the local Aircare program for pollution prevention
6	Review of Air Care program	A review of the local Aircare program for pollution prevention
7	Dynamotive's BioTherm and Bio-Oil: an example of pollution prevention	A review and analysis of the bio-oil process from a local company, Dynamotive
8	Life cycle analysis of common furnaces	A review on energy and cost analysis of furnaces with particular attention paid to the energy efficiency and air

		emission reduction
9	Applying integrated LCA and ERA analysis in alfalfa dehydration process	A review and outline of a LCA assessment for alfalfa drying process for the preparation of animal feed
10	Life cycle assessment of electric dryer versus paper towels	A review of LCA comparison of the two drying methods and a proposed work based on local paper and electricity sources

Current initiatives and future work

To co-ordinate the sustainability effort in the department in response to the university-wide sustainability initiatives, a sustainability committee was established in the Chemical and Biological Engineering Department in 2004 to accelerate all sustainability activities in the department in three areas: teaching, research and services. In a recent department faculty retreat, sustainability was the major topic under discussion with following initiatives identified for incorporating sustainability into the chemical engineering curriculum:

1. More sustainability content, especially on the non-engineering aspects such as concepts and qualitative approaches, should be implemented into relevant 2nd year engineering courses. On the other hand, chemical engineering should focus on implementing some engineering aspects of sustainability which are directly related to engineering practices and quantifiable.
2. The process for integrating sustainability components into each CHBE course should be done gradually, reflected in lectures, examples, assignments and case studies, and the integration will be a continuing process.
3. In addition to the lecture type courses, sustainability should be integrated into project-based lab courses and design courses. Specifically, more sustainability components should be implemented in the 4th year design projects by doing some in front assessment of the overall process performance using some sustainability metrics before the process is designed.
4. Graduate students should be encouraged to participate in campus-wide interdisciplinary research programs such as the Bridge program, and to increase the number of credits students can take from other departments to encourage students to take sustainability-related courses in the campus.

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