Incorporating Life-Cycle Assessment Issues for Green Energy Manufacturing Education

Dr. Richard Chiou, Drexel University (Eng. & Eng. Tech.)

Dr. Richard Chiou is Associate Professor within the Engineering Technology Department at Drexel University, Philadelphia, USA. He received his Ph.D. degree in the G.W. Woodruff School of Mechanical Engineering at Georgia Institute of Technology. His educational background is in manufacturing with an emphasis on mechatronics. In addition to his many years of industrial experience, he has taught many different engineering and technology courses at undergraduate and graduate levels. His tremendous research experience in manufacturing includes environmentally conscious manufacturing, Internet based robotics, and Web based quality. In the past years, he has been involved in sustainable manufacturing for maximizing energy and material recovery while minimizing environmental impact.

Dr. Yalcin Ertekin, Drexel University (Tech.)

Dr. Ertekin received his BS degree in mechanical engineering from Istanbul Technical University. He received MS degree in Production Management from Istanbul University. After working for Chrysler Truck Manufacturing Company in Turkey as a project engineer, he received dual MS degrees in engineering management and mechanical engineering from Missouri University of Science and Technology (MS&T), formerly the University of Missouri-Rolla. He worked for Toyota Motor Corporation as a quality assurance engineer for two years and lived in Toyota City, Japan. He received his Ph.D. in mechanical engineering from MS&T in 1999 while he worked as a quality engineer for Lumbee Enterprises in St. Louis, Missouri. His first teaching position was at the architectural and manufacturing Sciences department of Western Kentucky University. He was a faculty at Trine University teaching mainly graduate courses as well as undergraduate courses in engineering technology and mechanical engineering departments. He is currently teaching in Engineering Technology Program at Drexel University. His area of expertise is in CAD/CAM, Computer Numerical Control (CNC) machining, rapid prototyping and quality control. His research interest includes sensor based condition monitoring of CNC machining, machine tool accuracy characterization and enhancement, non-invasive surgical tool design, reverse engineering and bio materials.

Prof. Tzu-Liang Bill Tseng, University of Texas, El Paso

Dr. Tseng is a Professor and Chair of Industrial, Manufacturing and Systems Engineering at UTEP. His research focuses on the computational intelligence, data mining, bio- informatics and advanced manufacturing. Dr. Tseng published in many refereed journals such as IEEE Transactions, IIE Transaction, Journal of Manufacturing Systems and others. He has been serving as a principle investigator of many research projects, funded by NSF, NASA, DoEd, KSEF and LMC. He is currently serving as an editor of Journal of Computer Standards & Interfaces.

Mr. Shraman Kadapa, Drexel University (Mechanical Eng. & Eng. Tech.)

Shraman Kadapa completed his bachelor's degree in mechanical engineering from Purdue University, West Lafayette. He is currently pursuing a masters' degree in mechanical engineering and mechanics at Drexel University. He is a research and teaching assistant in the mechanical and mechatronics lab at Drexel. He is also a researcher in Scalable Autonomous Systems Lab. His research interests are mainly in robotics which include motion planning and localization of ground robots.

Mr. Smarth H Chadha

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Abstract

This paper describes the incorporation of life cycle assessment practices for teaching students from a variety of engineering disciplines in design and manufacturing. Green energy manufacturing is an emerging field and also provides a sustainable development model for modern manufacturing industries. Sustainable green manufacturing encompasses the design of manufacturing processes to prioritize energy conservation, pollution prevention or reduction, and increased health and safety of communities, employees, and consumers. In this age of global warming and diminishing fossil fuel stores, society is becoming increasingly aware that seemingly small decisions can have surprisingly far-reaching implications on the environment and future generations. Accordingly, today's engineers must approach design problems with a holistic, broad view of the impacts, environmental and otherwise, of their solutions. The notion of life cycle provides a structured, comprehensive approach for assessing the impact of an engineering solution, whether it takes the form of a product, a service, or a process. An engineering solution's life cycle includes all of the inter-related stages of its existence, from design to manufacturing and, ultimately, disposal. Life cycle is commonly used to assess environmental impact in each of these stages. However, this full "cradle-to-grave" view of an engineering solution's life span facilitates comprehensive evaluation along other equally important dimensions, such as cost, resource requirements, manufacturability, serviceability and even social impact. Academic disciplines such as industrial ecology and life cycle assessment, which are part this incorporation, are essential in helping engineers understand the importance of using scientific assessment to evaluate systematic sustainability impacts. The overall goal of this work is to share more details of this process and broaden the thinking of sustainability for engineering education.

1. Introduction

This paper describes the incorporation of life cycle assessment in teaching manufacturing at Drexel University. The goal of the engineering technology program is to develop advanced level practitioners in industry who are interested in developing green knowledge to meet evolving workforce demands, seeking professional development, expanding opportunities for professional advancement, or pursuing a managerial position[1-3]. To support this goal, the courses are restructured to enable students to understand life cycle assessment and therefore make green decisions when selecting and implementing a sustainable design plan for a particular industrial application through emerging green manufacturing. One of the key challenges in restructuring the traditional courses in design and manufacturing is an emphasis on life cycle assessment simulation experience for enhancing student learning on green manufacturing. To provide online simulation experience with network protocols, experiments with an industry-standard modeling tool GABI is used. Hence the teaching of green and sustainable manufacturing is an excellent opportunity to teach about research and innovations in industrial settings[4-10].

With increased societal and industrial interest in reducing the environmental impact of human activity, the need for environmentally conscious manufacturing has become more pronounced.

While there have been considerable national and international efforts in recent years, including ISO 14000, corporations are only now beginning to recognize the need to train product and manufacturing engineers in the tools and techniques of design for environmental impact. Engineers have tremendous influence on the environmental impact of products at all life stages including the materials used, energy consumed and pollution generated during manufacturing, distribution and use. In addition, they can have a definite impact on the ease with which a product can be reused, remanufactured or recycled prior to disposal. The project described in this paper is intended to inform students of one particular tool for design for environment known as life cycle analysis (LCA). This technique examines each life cycle stage of a product from material extraction to product disposal to determine the greatest environmental impacts in the product's life cycle. With this information engineers can focus their efforts for environmental improvement. In recent years there have been a large number of examples of LCA being used for engineering design applications[11-15].

To minimize the impact of engineering activities on the environment, it is critical that students develop skills to approach engineering from a green product system's perspective. These skills include detailed analyses of the entire life cycle for products, processes, and systems by considering materials extraction, manufacturing, distribution, disposal and the associated environmental impacts, which necessarily crosses engineering disciplines. For the project described here, students conduct a LCA of a solar panel actually used in the laboratory course with the intent of providing practical recommendations for environmental improvement. It is important to point out that the focus of the project is to acquaint students with the LCA approach in conjunction with the details of the solar panel life cycle. This paper begins with a brief explanation of life cycle assessment, including streamlined life cycle approaches. In addition, the project uses GABI software to provide much of the data for the analysis.

The Accreditation Board for Engineering and Technology (ABET) is charged with the task of "Quality assurance in higher education" for programs in applied science, computing, engineering, and technology. Institutions pursuing accreditation must demonstrate that the program meets a set of general criteria. Of particular interest are the requirements of Criteria #2, #3, and #5, which are focused on Program Educational Objectives, Program Outcomes and Assessment, and Faculty[16-17]. These requirements include:

1. A process based on the needs of the program's various constituencies in which the objectives are determined and periodically evaluated (Criterion #2);
2. The students in the program must attain "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability" (Criterion #3); and
3. The overall competence of the faculty may be judged by such factors as education, diversity of backgrounds, engineering experience, teaching experience, ability to communicate, enthusiasm for developing more effective programs, level of scholarship, participation in professional societies, and licensure as professional engineers (Criterion #5).

The paper presents the experience in teaching the course renewable energy systems incorporated with life cycle assessment education component[18-24]. The class was taught for 10 weekly lectures of 3-hour each which represent 11 weeks on a regular quarter. The course learning outcomes are:

1. Understand the main sources of energy, energy efficiency, and their primary applications in the US and the world, 2. Describe the challenges and problems associated with the use of various energy sources, including fossil fuels, with regard to future supply and the industry, 3. Evaluate economic efficiency and compare small scale energy projects using major economic measures of pay-back period, simple rate of return, net present value, internal rate of return, 4. Conduct life cycle assessment and evaluate manufacturing energy consumption and determine methods to increase energy efficiency, and 5. Relate properly their hands-on laboratory experiences to solving real-world clean energy and energy efficiency engineering problems. This allows the students to understand how these products are made so they can understand further on how they are manufactured and recycled.

2. Overview of the Life Cycle Assessment Education

Life Cycle Analysis (LCA) is a methodology to quantitatively assess the overall environmental impact of products, processes, and systems. LCA is an invaluable tool for assessment of environmental impact based both on data and the entire life cycle. EET 320 Renewable Energy Systems, is an upper-level undergraduate course at Drexel University which instructs students on the concepts and methods of LCA. This class is available for students from all twelve (12) disciplines in the College of Engineering as part of the Green Energy Manufacturing Program which strives to increase student awareness regarding the impact of engineering practice on the environment as well as to teach students engineering design and analytical skills to minimize such impacts. This class provides an excellent opportunity to develop both systems-based perspectives and multidisciplinary team skills.

The class was primarily taught in a traditional lecture-practicum format to build up the concepts in clean energy and energy efficiency, and skills required for a final multidisciplinary team LCA project. The learning objectives, grading metrics, and syllabus for the class are included for reference in the appendix. Since no textbook was found to cover the course material appropriately across the disciplines, a wide variety of materials (book chapters, journal and newspaper articles, corporate product information, web databases, and software manuals) were provided to the students to complement the lectures. The class was taught by faculty with disciplinary backgrounds in materials science and chemical engineering. The primary instructor also has several years of experience in Design for Environment (DfE) and Life Cycle Analysis methods practiced currently in industry. The use of faculty from other disciplines was considered for specific topics within this course, but unfortunately, the concepts covered are not commonly known or used by most engineering faculty. Therefore, appropriate multidisciplinary faculty were not available at this institution to provide significant value to the class. The use of industrial practitioners and/or faculty expertise from other institutions would be valuable to augment the course content with regard to specific disciplinary concepts.

Because all of the life cycles phases of these products were considered, the student knowledge from different disciplines was important for a thorough analysis. Generally, mechanical engineering students were able to comment on mechanical design and processing. Industrial systems engineers had insights into manufacturing processes, logistics, and transportation. Chemical and materials engineers provided detailed understanding of the materials and chemical processes required for these products. The civil/environmental engineering students were able to relate the outputs from the products and processes to environmental effects.

Even simple products, like those above, selected by the student teams are complex to model thoroughly, so the LCA software was critical for the quantitative analysis; the size of the team allowed good coverage for all aspects of the product. The students were required to identify their specific roles within the team, complete the analysis, and present the analysis in report format as well as a 20 minute presentation to the class. To encourage teamwork within the multidisciplinary project, the assessment of the students was based on several components. 40% of the project grade was given to the project team as a whole for the written report and oral presentation, 40% of the grade was based on the individual roles that the students assigned themselves on their team, and 20% of the grade was based on the students' peer assessment of the contributions of the other members of their team.

The course has an applied learning focus, offering flexibility to the students through an online learning environment. Since the concepts of online course are best conveyed through application-based learning, the course is divided into two components: a blackboard lecture component and an associative virtual LCA laboratory component. The virtual laboratory component is central to the course and is available to the students. This allows the students the freedom to explore the concepts of LCA without time constraints inhibiting learning. In order to provide an enhanced virtual laboratory experience, the students work with real world industrial case studies associated with green manufacturing.

Environmentally Benign Manufacturing

Students learn the introduction of the Environmentally Benign Manufacturing before they start to learn life cycle assessment. Specially designed assignments and projects have been developed for the course as a part of this practicum, and are necessary to complete many of the exercises in the course. Generally speaking, manufacturing is to convert materials into products. The manufacturing processes provide the job opportunities for people. The products made by manufacturing are to improve our standard of living. To increase the value and quality of the products, supply chain and services have to be involved with the manufacturing processes. One of the outputs must include waste from manufacturing processes. The shadow side of manufacturing needs to be addressed first, such as environmental issues and excess of energy used in industry.

The fundamental issue in environmentally conscious manufacturing is to align manufacturing needs with environmental issues. That is, how do we manufacture market-competitive products without harming the air, water, or soil on planet Earth? How do we motivate companies to behave unilaterally to adopt environmentally benign manufacturing practices? Will nation-states unilaterally recognize the need to impose environmental standards on companies manufacturing products within their national boundaries? Recent experience informs us that progress is being made on each of these fronts, but that we have a long way to go to fully protect the environment from the offenses committed by the worldwide manufacturing community.

Design for the Environment

Students have to learn what the Design for Environment (DfE) is in the course. Design for Environment has the common known acronym DfE and can be viewed in different ways. DfE is a philosophy that advocates that consideration be given to the environment when developing new products and processes. DfE is an engineering design initiative that promotes environmentally sound decisions at every step of the production process from chemical design, process engineering, procurement practices, and end product specification to post-use disposal. The concept is developing in the environmental/engineering fields and is beginning to gain public recognition. Therefore, DfE is about industry improving and optimizing the environmental performance of products, impacts on human health, associated risk, product and process costs, efficient use of materials, waste and pollution prevention, and energy conservation.

During the past years, growth of interest and initiatives around the concept of pollution prevention and toxics use reduction has been significant. Firms around the world are beginning to recognize that it is far more efficient to prevent the generation of industrial wastes than to manage the wastes once they are produced. In the U.S., environmental engineers increasingly are engaging production engineers around reduction of waste streams from manufacturing processes. Yet this is only one avenue for bringing about environmentally sound production processes. The opportunity to consider environmental effects at the earliest design points in the development of new products or the redesign of current production processes opens up an exciting new area of professional work.

The industrial ecology view promotes sustainable manufacturing through the modeling of industrial processes after the material and energy flows of the natural environment. An industrial ecosystem follows a cyclic model in which the consumption of energy and materials is optimized, waste generation is minimized, and the byproducts of one process become raw material for another. DfE pursues industrial ecology principles by requiring that industrial designers and managers think in terms of cycles or complex systems rather than traditional linear process flow diagrams. Industry is beginning to consider the environmental impact of a product throughout its life cycle, primarily because of regulatory trends, rising treatment and disposal costs. Corporations are also recognizing the potential economic advantage of DfE. But more training, technical information, and industry-specific knowledge of DfE are needed to bring about its broad-scale implementation. Efforts to develop and integrate DfE with life cycle assessment (LCA) into the production of products and services are under way in the public and private sectors.

Life Cycle Assessment

From the outline of the lecture, students learned what LCA is, Why use LCA, and what it can be used for business benefits. LCA is a tool to measure, assess, and manage the environmental performance of a product from raw material through production, use and end-of-life phase. As environmental awareness increases, industries and businesses are assessing how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. Many businesses have responded to this awareness by providing “greener” products and using “greener” processes. The environmental performance of products and processes has become a key issue, which is why some companies are investigating ways to minimize their effects on the environment. Many companies have found it advantageous to explore ways of moving *beyond* compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. One such tool is LCA. As shown in Figure 1, this concept considers the entire life cycle of a product. Every year, more and more companies are becoming concerned with the environmental impact of their activities. Currently, the main driving force is the need for companies to stay competitive in the marketplace.

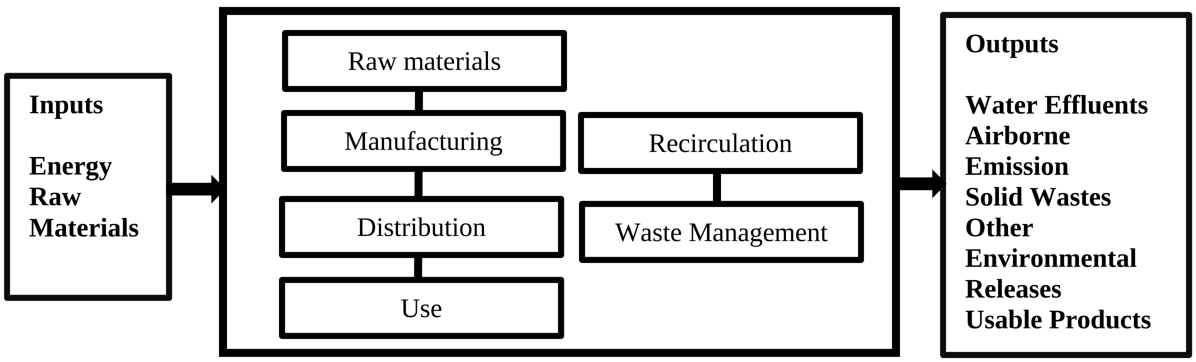

Figure 1: The Product Life Cycle

LCA practitioners define how data should be organized in terms of a *functional unit* that appropriately describes the function of the product or process being studied. Careful selection of the functional unit to measure and display the LCA results will improve the accuracy of the study and the usefulness of the results. The life cycle of a product begins with the removal of raw materials and energy sources from the earth. For instance, the harvesting of trees or the mining of nonrenewable materials would be considered raw materials acquisition. Transportation of these materials from the point of acquisition to the point of processing is also included in this stage. During the manufacturing stage, raw materials are transformed into a product or package. The product or package is then delivered to the consumer. The manufacturing stage consists of three steps: Materials manufacture, Product fabrication, and Filling/packaging/distribution. For Use /Reuse /Maintenance, this stage involves the consumer’s actual use, reuse, and maintenance of the product. Once the product is distributed to the consumer, all activities associated with the useful life of the product are included in this stage. This includes energy demands and environmental wastes from both product storage and consumption. The product or material may need to be reconditioned, repaired or serviced so that it will maintain its performance. When the consumer no longer needs the product, the product will be recycled or disposed. Finally, the recycle/waste management stage includes the energy requirements and environmental wastes associated with disposition of the product or material.

Students learned LCA to assess product development options and establish baseline information for a process. A key application of LCA is to establish a baseline of information on an entire system given current or predicted practices in the manufacture, use, and disposal of the product or category of products. In some cases, it may suffice to establish a baseline for certain processes associated with a product or package. This baseline would consist of the energy and resource requirements and the environmental loadings from the product or process systems that are analyzed. The baseline information is valuable for initiating improvement analysis by applying specific changes to the baseline system. Therefore, LCA can be used to inform industry, government, and consumers on the tradeoffs of alternative processes, products, and materials. The data can give industry direction in decisions regarding production materials and processes and create a better informed public regarding environmental issues and consumer choices.

With features refined through experience on thousands of PE consulting projects, GaBi supports every stage of a LCA, from data collection and organization to presentation of results and stakeholder engagement. GaBi updates all material, energy, and emissions flows, as well as defined monetary values, working time and social issues, giving instant performance accounting in environmental impact categories. GaBi allows rapid modeling of complex processes and different production options with a modular architecture. This architecture makes it easy to add other data such as economic cost or social impact information to a model, making GaBi a useful tool for life cycle assessment. The GaBi platform is complemented by the most comprehensive, up-to-date Life Cycle Inventory database available. The databases maintained by PE provide over 2,000 cradle-to-gate material data sets, 8,000 intermediary chemical process models, and thousands of LCA projects from quality-controlled industry projects. The data set contained in this educational version of GaBi Education, which is a small fraction of the available data within the professional engineers. The simulation software GaBi provides an extensive introduction to LCA methodology and outlines step by step procedures for building a model with GaBi. The students had one example (a paper clip) for life cycle assessment throughout the software tutorial series posted in website.

Life Cycle Assessment Project: Solar Cell Module

The first GaBi tutorial given to the students was the modelling of a simple, single component, paper clip. The next phase of life cycle analysis challenged students with a more complex model. They were given a project of creating the plan for a solar cell module based on the lessons they learned in the previous model. The solar cell module consists of numerous parts, each requiring various materials and processes. Students learned the modelling of acquisition of materials, processes, assembly, use, disassembly and disposal that gave them a hands-on of real life problems. The experience was complete with all requirements of the ISO standards, such as the goal and scope definition, inventory analysis and impact analysis.

By incorporating these factors, we can clearly see the effects on people and the environment. It is important to understand the different stages before analyzing the data. The raw material acquisition is understanding how we can obtain the materials, whether it be through mining, deforestation, etc. Next, it is important to understand how we are going to process those materials. Do they need to be melted? This would require energy and emit toxins or chemicals to the environment. After this it is important to understand how we manufacture the different parts to obtain the desired product. In the case of the solar cell module we need to obtain copper, plastic and several other raw materials. Next, the product has to get to the consumer. This is usually done with planes, trains and cars that emit CO2 into the atmosphere. Finally, in the case of a solar cell module, it requires electricity to run which is another factor to consider. To obtain the electricity, we had to use other natural resources (most likely) which is detrimental to the environment. Finally, once the product has been used, and no longer works, we must dispose of it. It is important to note if a product can be recycled and what will be done with the different parts. This flow of events can be seen in image two below. This image provides a job of showing how a product moves through all the stages of its life and what goes into a life cycle analysis. The main purpose of this paper is intended to evaluate and analyze the environmental effects associated with a solar cell module over its life cycle. This life cycle assessment simulation model helps us to evaluate the energy and materials used in the production of this product from cradle to grave. A complete system is taken into account from the raw material acquisition phase to the product recycle/disposal. The usage of reusability techniques would help to reduce the environmental footprint. The solar cell module LCA includes simulation results from Gabi Software from the raw material acquisition phase to the final product with recycle/disposal phase.

With swift exhaustion of natural resources, it is imperative to evaluate and reduce the impact of energy consumption to have a sustainable environment. Life cycle assessment keeps track of the energy and materials used in the manufacturing of the product from cradle to grave. This ensures each and every factor is taken into account to determine its effects into the environment. This LCA assessment includes raw material acquisition, material processing, product design, product manufacturing, product distribution and the product use and disposal phases. The wastes associated during the manufacturing of the product is identified to better understand its harmful effect to the environment. This in turn will help to improve the way the product is manufactured using greener ways. As silicon is the second most abundant element in the Earth's crust, it is important to create a life cycle assessment of a solar panel module.

Gabi software was used to run the simulations for the life cycle assessment for the solar cell module. At first, a flowchart was created which showed all the different phases associated with LCA. All the relevant data for every phase of the manufacturing of the solar panel was collected. This step involves an extensive research towards identifying all the raw materials required for manufacturing along with the manufacturing process itself. Once a flowchart is created, the input and output flows for each and every phase is recorded into the software. This flowchart includes raw material acquisition phase, material processing, product design, product manufacturing, product distribution and the product use and disposal phases. Once the input and output phase for each and every phase is recorded, the balance option on the Gabi software gives important facts about the emissions in the environment during the production of this solar panel module. The next section shows the results that were obtained when the simulation of the solar cell module was completed.

Figure 2 shows a schematic diagram of the production of the solar panel module. This includes all the different phases from cradle to grave. The top half from the schematic below represents the production of the solar panel. The bottom half from the schematic below represents the production of the module specifically. The input and output flows for each and every phase is recorded in the DB object of that particular phase. The first step is to produce metallurgical grade silicon. In order to process with a purity of 99%, silica sand is thermally reduced using petrol coke[25-27]. From MG-silicon Electronic grade silicon is produced from three different processing steps which include conversion of MG-silicon into gas, purification of gas using distillation and deposition of silicon in solid form. Using electronic grade silicon, single and multi-crystal silicon and silicon carbide is produced. This single crystal silicon is used to fabricate silicon wafers. Silicon solar cells are produced through silicon wafers.

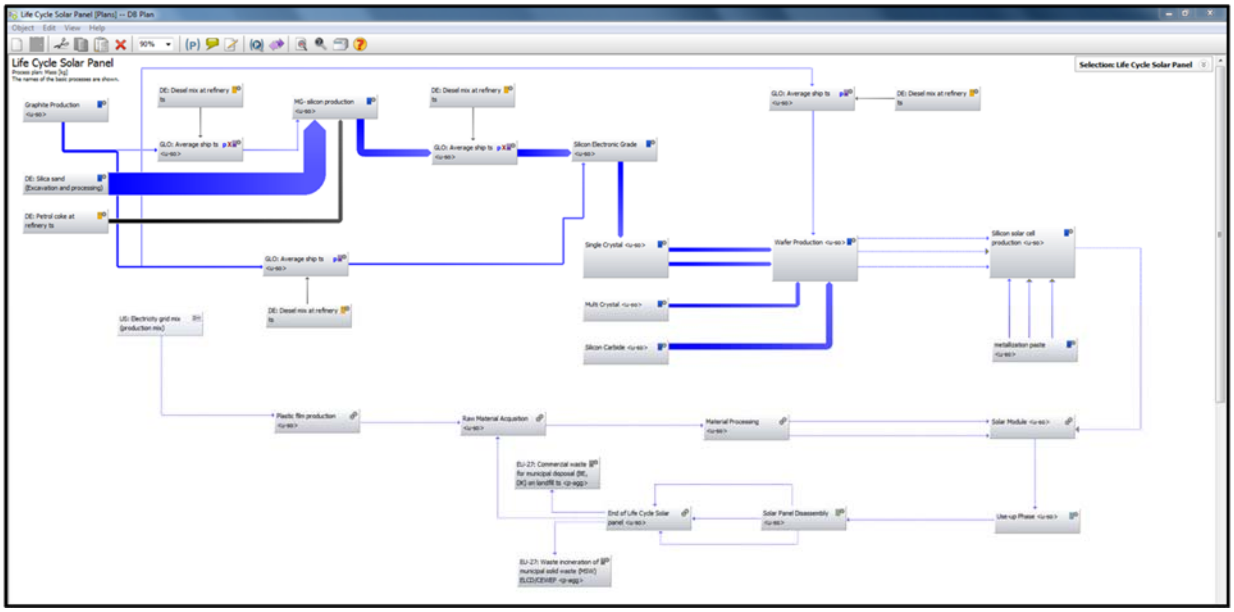

Figure 2: A schematic of the solar panel module from cradle to grave

Once the silicon solar cells are produced, the next part is to create the solar panel module. The plastic film is produced using polyethylene terephthalate granules. The laminate and the photovoltaic panel are taken from the production step to assembly phase. At the assembly phase, the plastic film, solar glass, photovoltaic panel and the solar cell are used to assemble a complete solar panel module. Figure 3 shows the final product that is modeled.

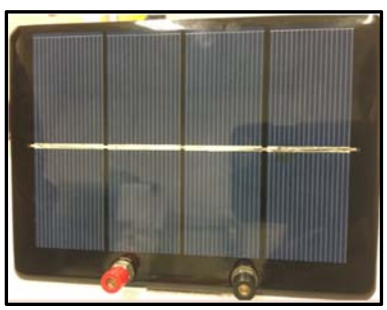

Figure 3: Final Product- Solar Panel Module

Once the production of a solar panel module is outlined, the important step is to think about end of life recyclability. The parts are first disassembled from the final product and then sent for recycling. This step will ensure at the end of life span; some parts of the solar panel module can be recycled and some parts can be disposed off. The recyclability for this product includes the plastic film, stainless steel screws and the solar glass which is sent back to the raw material acquisition phase where it is used to rebuild those parts. This will ensure recyclability which helps in reducing the emissions into the environment.

	Life Cycle Solar Panel
Flows	5.2E005
Resources	5.19E005
Others	
Deposited goods	9.9
Emissions to air	90.5
Emissions to fresh water	1.19E003
Emissions to sea water	1.25
Emissions to agricultural soil	5.47E-006
Emissions to industrial soil	1.25E-006

Figure 4: Emissions from Life Cycle Assessment of Solar Panel Module

	Life Cycle Solar Panel
Flows	5.2E005
Resources	5.19E005
Energy resources	4.53
Land use	
Material resources	5.19E005
Others	
Deposited goods	9.9
Radioactive waste	0.000383
Stockpile goods	9.9
Emissions to air	90.5
ecoinvent long-term to air	54.6
Heavy metals to air	0.0372
Inorganic emissions to air	29.8
Organic emissions to air (group VOC)	0.238
Other emissions to air	5.62
Particles to air	0.226
Pesticides to air	6.87E-009
Radioactive emissions to air	1.33E-014
Emissions to fresh water	1.19E003
Analytical measures to fresh water	4.62
ecoinvent long-term to fresh water	9.04
Heavy metals to fresh water	0.00352
Inorganic emissions to fresh water	1.06
Organic emissions to fresh water	0.00199
Other emissions to fresh water	1.17E003
Particles to fresh water	0.0285
Radioactive emissions to fresh water	
Emissions to sea water	1.25
Analytical measures to sea water	0.000116
Heavy metals to sea water	9.14E-006
Inorganic emissions to sea water	0.0964
Organic emissions to sea water	5.72E-005
Other emissions to sea water	1.15
Particles to sea water	0.00163
Radioactive emissions to sea water	
Emissions to agricultural soil	5.47E-006
Heavy metals to agricultural soil	5.47E-006
Inorganic emissions to agricultural soil	6.61E-013
Emissions to industrial soil	1.25E-006
Heavy metals to industrial soil	9.58E-010
Inorganic emissions to industrial soil	1.25E-006
Organic emissions to industrial soil	2.04E-010

Figure 5: Expanded emissions to environment from Life Cycle Assessment of Solar Panel Module

Results

The flowchart above helps to generate results which show the harmful effects on the environment for producing a solar panel module. Figure 4 portrays the amount of emissions to air, fresh water, sea water, agricultural soil and industrial soil that occur during the production of the complete solar panel module. The data shows that the emissions to fresh water is the most and needs to be taken care off to reduce the adverse effects on the environment.

Figure 5 gives an expanded detailed data of the emissions to environment. Using this data set, it can be narrowed down to the specific factors that affect the most. From this information, possible improvements can be done to ensure these numbers are under control. As seen from figure 5 it can be seen that other emissions to fresh water are the most. It can also be observed that the radioactive waste is 0.000383. This is a low number which is good for the environment. Going further in the analysis, it can be seen that Eco invent long-term emissions to air play a very significant role in discharges in air category. The emissions to industrial and agricultural soil are relatively low which is a positive sign. The following figures graphically represent the steps during production that lead to harmful effects on humans and the environment specifically. This analysis helps to identify and improve those factors that are contributing towards these high numbers.

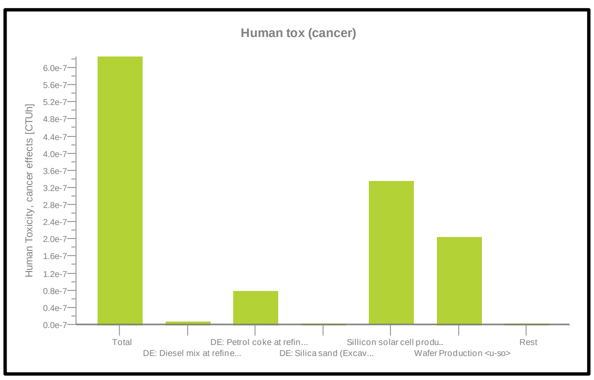

Figure 6: Human toxicity (cancer)

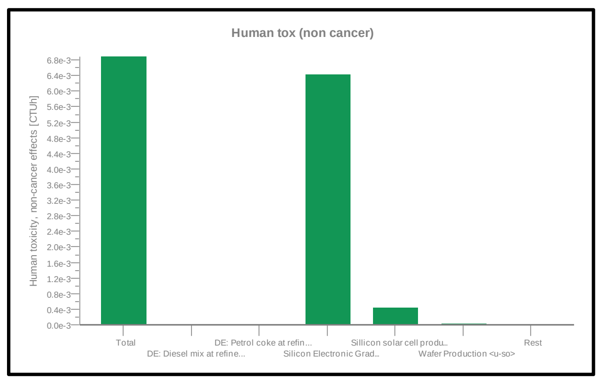

Figure 7: Human toxicity (non-cancer)

Figures 6 and 7 show the total human toxicity potential from the life cycle assessment of the solar panel module. Figure 6 shows that the human toxicity potential is the most in the silicon solar cell production compared to other production steps. This potential means that harmful chemicals are released into the environment during silicon solar cell production which can lead to cancer. Similarly, figure 8 shows that production of electronic grade silicon leads to the most amount of human toxicity potential which is non-cancer related.

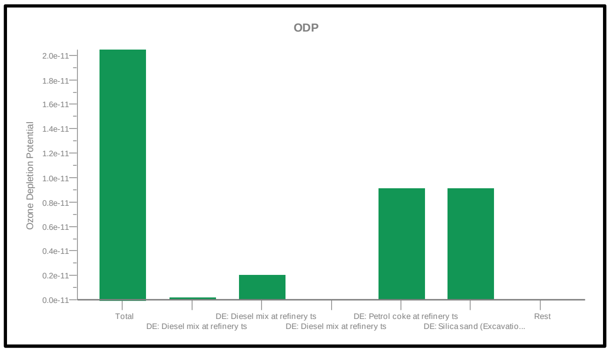

Figure 8: Ozone depletion potential

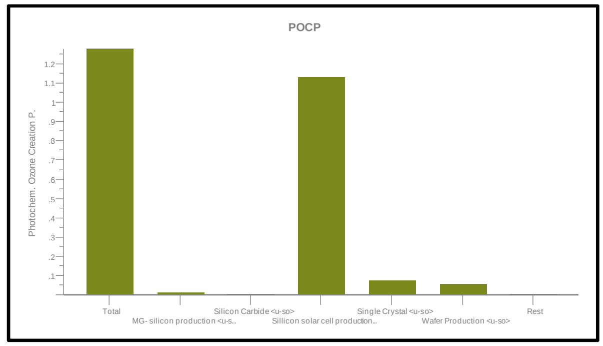

Figure 9: Photochemical ozone creation potential

Figures 8 and 9 represent values related to the ozone layer. Figure 8 shows the ozone layer depletion potential. These numbers represent the amount of degradation of the ozone layer that is occurring. Using raw materials like petrol coke at refinery and silica sand for the production of solar cells leads to the depletion of the ozone layer. These raw materials lead to a big effect compared to other materials and production steps. Figure 9 showcases the photochemical ozone creation potential. This potential is defined as the ability of volatile organic compounds to significantly help in creating the ozone layer. The plot above shows that silicon solar cell production step has the highest POCP levels.

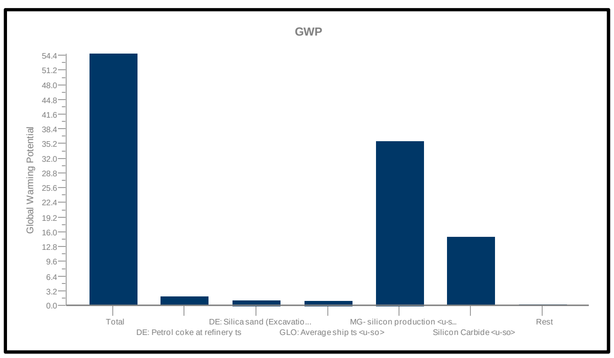

Figure 10: Global warming potential

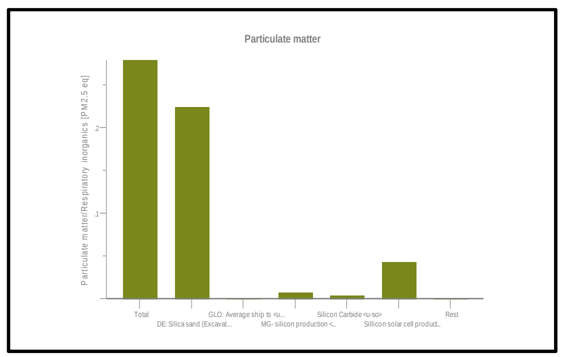

Figure 11: Particulate matter effects

Figure 10 showcases the global warming potential which is an indication of the amount of energy absorbed by 1 ton of a gas relative to the emissions of 1 ton of carbon dioxide. The above figure shows that global warming potential is the most in the production of metallurgical grade silicon. A higher global warming potential indicates that gas heats the Earth compared to that of carbon dioxide. This potential should be as low as possible to ensure a greener environment. Particulate matter tells the total solid and liquid particles that are suspended in air. These hazardous emissions lead to harmful effects to the atmosphere. Figure 11 shows silica sand being the major contributor of high levels of particulate matter. This particulate matter contains organic and inorganic emissions which lead to adverse effects to the air.

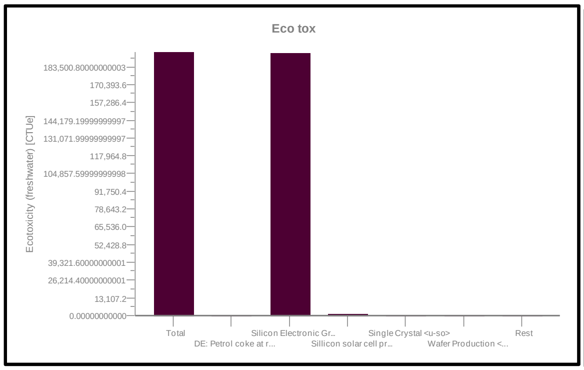

Figure 12: Eco toxicity effects

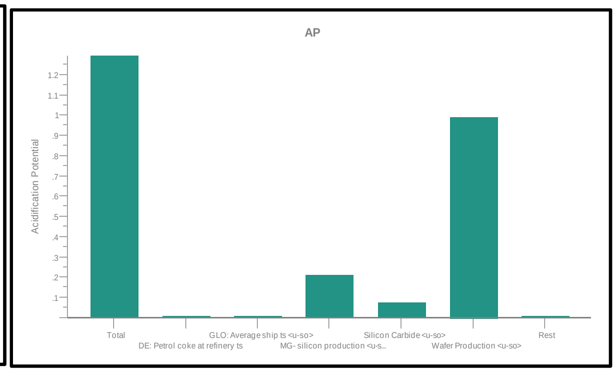

Figure 13: Acidification potential effects

Figure 12 represents the amount of stressors such as biological and chemical stressors that affect the ecosystems. These effects lead to a shift in the balance of the ecosystem. It can be seen that the production of electronic grade silicon contributes almost all the ecotoxity potential for the production of solar panel module. Figures 13 and 14 show the acidification and eutrophication potential numbers for some of the significant contributing factors. During the wafer production, the acidification potential is significantly higher than other production steps. This shows the air pollution levels rise during the silicon wafer production phase. Depletion of ozone in water levels are high which leads to the death of aquatic animals which in turn affects significantly towards the balance of the ecosystem.

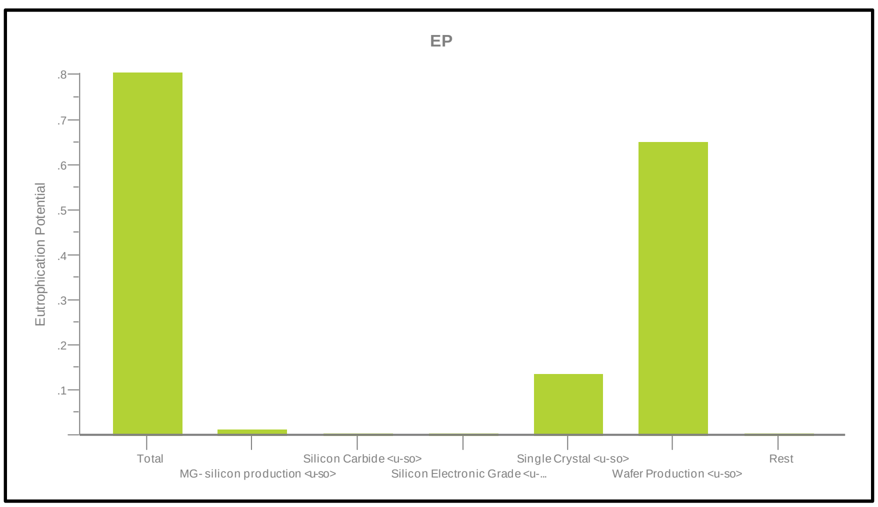

Figure 14: Eutrophication potential effects

The life cycle assessment helps to identify the specific emissions on environment. LCA helps to identify and evaluate the harmful effects each and every production step has on the environment. Care must be taken to ensure the emissions to fresh water are reduced which would help in improving the quality of the environment. The eutrophication and acidification potential numbers should be looked at to reduce the imbalance in the ecosystem. Looking at these numbers, if proper action is taken, a greener future can be accomplished.

Assessment and Evaluation

Overall the feedback received at the end of the term from the participating students was largely positive with regards to the experiments involving renewable energy systems. Many students appreciated the ease with which a solar panel can be designed and tested in an attempt to deal with issues as they arise. Without a doubt all of the students were exposed to the green product topic surrounding materials, fabrication, testing, and measurements in life cycle assessment. Students are required to analyze, design, simulate, and build a completely functional system by the end-of-term project. The goal of the class project was achieved to enhance student understanding of the fundamental concept of design-for-environment (dfE) and hands-on learning of green energy manufacturing. Students understood the design for the environment by improving and optimizing the environmental performance of products, impact on human health, associated energy, and material and process costs. Students commented that they enjoyed working in such green energy manufacturing project with hands-on laboratory experiments. Students commented that they enjoyed working in the LCA virtual laboratory. Students' evaluation was conducted at the last week of the class (4.2/5.0).

A network analysis approach was also conducted to analyze online student interactions. The site was developed with Google Groups to provide students the opportunity to discuss, share, and learn both from and with one another on topics related to green energy manufacturing, including life cycle assessment. The study demonstrates that the online site supports interaction among the undergraduate students. The online assessment result was consistent with the class student evaluation. In particular, online students shared course-related advice and information across the sites as a whole and were selective with those whom they sought out for support, information, or guidance. This study has implications for future research to determine why students chose to use the site to interact with their peers and what these interactions provided them. Such data could inform the ways the site helped support students both in their advancement in the program, and could be useful in assisting future development of such sites and similar learning spaces.

3. Conclusions

The course EET 320 Renewable Energy Systems convers green energy manufacturing concepts and it provides an understanding in sustainability by incorporating life cycle assessment issues. Towards this, weekly lecture and assignment were incorporated within this course that students need to complete at the end each week session. In addition to the weekly discussions, the facility is equipped with collecting facility usage data. The course is intended to provide an in-depth overview of sustainable and green manufacturing. Upon successful completion of the course in this discipline, the students were able to achieve learning outcomes: 1. Understand life cycle analysis and clean manufacturing, 2. Understand recycling, hazardous materials, and pollution prevention, 3. Identify the characteristics of hazardous substances and waste materials, and 4. Understand the design for the environment by improving and optimizing the environmental performance of products, impact on human health, associated risks, and product and process costs. Course reviews by students were very positive. The benefits of an active learning model were derived. Students mentioned appropriate time involved with the homework assignments and exams. Many commented positively about their knowledge gained related to their current jobs in their own companies. The results showed the highly supportive evidence towards the intended online course outcomes.

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