SYMPOSIUM G

Life-Cycle Analysis Tools for "Green" Materials and Process Selection

November 28 - 30, 2005

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* Invited paper

SESSION G1/S1: Joint Session: LCA Principles
Chair: Stella Papasavva
Monday Morning, November 28, 2005
Room 203 (Hynes)

8:30 AM *G1.1/S1.1

Integration and application of Life Cycle Assessment within the design of products and processes - an important step towards sustainable development. Marc Binder and Harald Florin; PE Europe GmbH, Leinfelden-Echterdingen, Germany.

Sustainable development is the strategy to find the balance between the needs of present generation without compromising the ability of future generations to meet their own needs. Sustainable development integrates ecology and economic progress and is aiming for social equality between and within generations. This presentation will give a brief introduction into sustainable development focusing on Life Cycle Assessment (LCA), the most acknowledged and comprehensive method to realize and assess the environmental aspect of sustainable development on a quantitative basis. The methodology of LCA will be presented showing the audience the necessary step when performing an LCA. It will show why it is important to consider the total life cycle and include various environmental impact categories and not only consider primary energy demand and CO2 emissions. The second emphasis will be on the demonstration of a time and resource efficient way to integrate LCA into the design process using existing sources of information (companies internal documentation systems, public-/ commercial LCI databases, and tools). It will be shown how to perform an LCA in an efficient way, which information in what level of detail is necessary, who needs to be involved, what steps have to be performed, and how the study can be used and communicated within the company and to external stakeholders. Goal of this presentation is to give the audience an impression of the possibilities of LCA in general, its role within sustainable development, and show them the relation between effort and benefit of the application of the methodology of LCA within the design process.

9:00 AM *G1.2/S1.2

A Sequential Interindustry Model as an LCA Tool. Stephen H. Levine[1] and Thomas P. Gloria[2]; [1]Civil and Environmental Engineering, Tufts University, Medford, Massachusetts; [2]Five Winds International, Newton, Massachusetts.

LCA is a systems level approach to the evaluation of environmental impacts. Combining LCA with economic input-output (EIO) techniques facilitates the extension of the system boundaries to include all the economic activity indirectly as well as directly required to produce a product or a project. However, traditional EIO models, similar to LCA, provide a minimal temporal description of environmental impact. Yet such a description can be important in determining the environmental burden that the product or project may generate. This is especially true when the life span of the product or project is of long duration. Additionally, inclusion of indirect requirements for production extends the relevant time frame well before the product or project is completed. Probably the extreme example of a project whose production phase is of long duration is the proposed transition from a hydrocarbon to a hydrogen-based economy. Government estimates for this transition are on the order of forty years. The Sequential Interindustry Model (SIM) is an input-output model that by accounting for the time required by production and construction activities can provide the basis for a temporally explicit description of environmental impacts. Recent extensions of the model allow it to account for those resources required during the use and retirement phases as well as the production phase of a product or project. For many products and projects the use phase is of far greater duration than the production phase, even when indirect requirements are accounted for. Thus while all the production activities directly or indirectly required for an automobile may occur over several months the automobile may be on the road for many years. This paper will describe how SIM might be used in conjunction with LCA to strengthen the temporal component of the resulting analysis.

9:30 AM *G1.3/S1.3

The use of Life Cycle Engineering/ Life Cycle Assessment within the design process of production facilities; A business case: Different options of handling overspray. Marc Binder, Johannes Kreissig and Harald Florin; PE Europe GmbH, Leinfelden-Echterdingen, Germany.

This presentation will illustrate how to expand the view by considering the total life cycle in an efficient way into the decision making process and why it is important to do so. The business case will show, how the - ecological and - economic aspects considering the total life cycle of different design options have been considered when determining the preferable design options out of an holistic point of view. Life Cycle Engineering (LCE)/ Life Cycle Assessment (LCA) integrated in the design Process LCE methodology is evaluating ecological, technical and economic aspects considering the total life cycle of processes/products. LCA studies are the basis for the ecological evaluation within LCE. LCE studies are based on material and energy flow information needed while running the facilities or for producing products. LCE is a simulation tool show optimization potentials as well as supporting the decision making process within the design phase. As various databases hold information on ecological impacts of material- and energy production and information on the economic values is available within the involved companies, time consuming research on basic materials and energies is not necessary. Therefore first estimations on scenarios can be made within days to support the decision process not causing any time delay. LCE studies can be conducted within the design process and on existing facilities/products. If LCE is used within the design process optimization potentials can be shown in early stages of the design phase of facilities/products. Integration of LCE within early stages of the design ensures an efficient way of improving the ecological profile of processes and products and reducing the overall costs considering the total life cycle. Business case: Overspray handling of new rear axle paint shop of DaimlerChrysler The methodology of LCE has been integrated into the design process of the new rear axle paint shop of DaimlerChrysler focusing on the handling of the overspray. The design of the facilities have been modeled according to the material and energy flow. This enables the user to run scenario analysis for different design options based on the process flow model. Different design options have been analyzed and arguments were made explicit to support the decision making process. As LCE was part of the whole design process from the beginning, the effort for all participants could have been minimized. Conclusions The case study has shown that the integration of LCE into the design process provides additional information and is not causing any delay of the decision making process. LCE enables a transparent presentation of the economics and ecological impacts on a process bases. Optimization potentials, ecological and economic, can be shown at all stages of the design phase and result in reducing the overall costs and environmental burdens caused by the paint process.

10:30 AM *G1.4/S1.4

Environmental Assessment of Micro/Nano Production in a Life Cycle Perspective. Stig Irving Olsen, Dep. Manufacturing Engineering and Management, Technical University of Denmark, Lyngby, Denmark.

The concept of life cycle assessment (LCA) is build upon the object of assessment, namely the functional unit, i.e. all impacts etc. are related to a specific service or function in the society. In a LCA context, the assessment of emerging technologies like Nanotechnology is challenging due to a number of knowledge gaps. It may not be known exactly what is the function (or functional unit) or what the technology may substitute and production may still be at an experimental level, raising questions about technology or materials choice. For prospective LCA studies methodologies like consequential LCA may be useful because future changes are taken into account. However, it still does not suffice for emerging technologies. In a recent "Green Technology Foresight" project a methodology was developed based on five elements: Life-cycle thinking, systems approach, a broad dialogue based understanding of the environment, precaution as a principle and finally, prevention as preferred strategy. When assessing emerging technologies three levels should be considered. First order effects are connected directly to production, use and disposal. Second order are effects from interaction with other parts of the economy from more intelligent design and management of processes, products, services, product chains etc. and the effect on the stocks of products. An example could be dematerialisation. Rebound effects may be considered as third order effects, like when efficiency gains stimulate new demands, which balances or overcompensates the savings. In the Micro/Nano Production area a range of new possibilities arise both within applications, production technology and materials. The Department of Manufacturing Engineering and Management at The Technical University of Denmark has staked on a joint effort in manufacturing engineering and environmental assessment for eco efficiency improvement. A review of knowledge and studies on environmental assessments in the micro/nano technology area is performed and will be used to further detail the general framework for assessment outlined above to be more specific for micro/nano production.

11:00 AM *G1.5/S1.5

Energy and the Environment: Perpetual Dilemma or Nanotechnology-Enabled Opportunity? Debra R. Rolison and Jeffrey W. Long; Surface Chemistry, Naval Research Laboratory, Washington, District of Columbia.

The global demand for the energy that sustains human-based activity drives extraction, production, and in-use processes that can compromise environmental quality. Yet the global and local environment can only be sustained, cleaned, and preserved through the expenditure of energy. A perpetual irony it may be, but thermodynamics demands that truism. Are there environmentally green opportunities that can be realized by re-thinking and re-designing energy production and power generation from a nanoscopic perspective? Multifunctional materials are prerequisite to deliver high performance in electrochemical power devices, but independent control of the elementary processes that give rise to energy-relevant functionalities is difficult-to-impossible with bulk materials. For example, even with decades of work, fuel cells still require the design of improved structures to maximize the effective area of the three-phase boundary as well as the transport of all species to and from it. These challenges are opportunities awaiting creative nanoarchitectural design. We describe the genesis of a carbon- and ionomer-free fuel-cell electrode in which an ultraporous nanoarchitecture that affects efficient transport of fuel is self-wired with a Pt-catalyzed, three-dimensional electron/proton nanowire.

11:30 AM G1.6/S1.6

Input/Output-But What Does It Really Mean? Mark Goedkoop[2] and Lise Laurin[1,3]; [1]EarthShift, Eliot, Maine; [2]PRe Consultants, bv, Amersfoort, Netherlands; [3]Sylvatica, North Berwick, Maine.

Input/Output databases and LCAs that rely on them exclusively (Input/Output LCA) or partially (hybrid LCA) are relatively new concepts in LCA. Unlike traditional LCA data that is collected for each material or process by painstakingly accounting for the kilograms and joules of everything going into them and the emissions caused by their extraction or manufacture, Input/Output LCA data is collected from national datasets for large sectors. Since the one thing we can easily track from one sector to another is money, the unit of measure is the dollar (or euro, or yen). The advantage of Input/Output databases is that they encompass all products produced in a particular region, and that they take into account impacts that are often ignored in traditional LCA, such as the impacts of marketing and legal activities. The disadvantage is that they provide very coarse data, making it impossible to see the difference between two different types of plastics, for example. The way around this disadvantage is to use a hybrid LCA—use specific data for the plastics and Input/Output data for the rest of the system. There is good input/output data available for the USA, Australia, Denmark and the Netherlands, and an EU database is in the works. In this paper we will explore the uses of Input/Output databases, the limitations and special considerations to take into account while using them, and interesting information we can gain from them.

11:45 AM G1.7/S1.7

Addressing Environmental Issues for the Automotive Industry. Stella Papasavva, [1]Chemical & Environmental Sciences Lab, General Motors, Warren, Michigan; [2]General Motors, Warren, Michigan.

The integration of environmental, social, and economic objectives into bussiness decisions and future planning is the path towards sustainable development. Industrial ecology is the integral part of the three components of sustainable developemnt. The principles of industrial ecology are founded in the way natural ecosystems behave. Industrial ecology examines ways to reduce and effectively manage resources in order to maximize economic benefits to the industry and minimize virgin material inputs. This presentation addressess the concept of industrial ecology within the automotive industry providing key areas where it can be implemented.

SESSION G2: Hydrogen Economy
Chair: Vasilis Fthenakis
Monday Afternoon, November 28, 2005
Room 303 (Hynes)

1:30 PM *G2.1

Implementing a Hydrogen Energy Infrastructure: Materials Issues and System Design. Joan Ogden, Institute of Transportation Studies, University of California-Davis, Davis, California.

Development of hydrogen infrastructure has been identified as a key barrier to implementing hydrogen as an energy carrier. Several recent studies of hydrogen infrastructure transitions have focused on the so-called "chicken and egg problem" of matching hydrogen supply to a growing demand. In this paper, we discuss how advances in materials science related to hydrogen storage, hydrogen production and fuel cells could radically change how a future hydrogen infrastructure is designed. For example, if more compact hydrogen storage could be developed that required a lower energy input, costs would be reduced and design improved in both hydrogen vehicles and in the fuel delivery system. With better fuel cell materials enabling more efficient fuel cell vehicles, less production hydrogen and delivery capacity would be required to serve the same number of vehicle miles traveled, reducing overall costs for a transition to hydrogen. Using a simplified model for hydrogen infrastructure design and cost, we explore some potential impacts of advances in materials, in terms of system design, cost, energy use, and greenhouse gas emissions.

2:00 PM *G2.2

Hydrogen as Fuel for Urban Transportation. Environmental Footprint of Different Hydrogen Production Routes and the Influence on the Total Life Cycle of FC Powered Transportation Systems: An LCA Case Study within CUTE. Marc Binder[1], Michael Faltenbacher[2] and Matthias Fischer[2]; [1]PE Europe GmbH, Leinfelden-Echterdingen, Germany; [2]Life Cycle Engineering, IKP University of Stuttgart, Stuttgart, Germany.

Since hydrogen became an important candidate for future fuel, hydrogen used fuel cell has been regarded as one of the new propulsion system. A consortium of industries, research institutes and several European cities launched the EU-project CUTE (Clean Urban Transport in Europe), whose aim is not only to develop and demonstrate 30 fuel cell busses and the accompanying infrastructure in 10 European cities, but also assess the environmental impacts. Within the project scope the potential of fuel cell powered transport systems for reducing environmental influences such as greenhouse effect, improving the quality of the atmosphere and conserving fossil resources is assessed. This first large scale test run of fuel cell transportation systems is the best possible information base to give real life numbers about environmental impacts of a fuel cell system including hydrogen used as fuel. Meanwhile the use of hydrogen fuel is mostly considered as environmental friendly. However a statement about the actual environmental impacts is only possible by regarding the entire Life Cycle of the hydrogen, which include its production and use. Within CUTE different routes of the hydrogen production have been assessed: hydrogen production via electrolysis and steam reforming, considering different boundary conditions, e.g. country specific energy production/ supply, different ways for electricity production (e.g. wind power, geothermal energy etc.) etc. This presentation will show the environmental footprint of these routes (Life Cycle Assessment results), which enable the comparison of the environmental impacts of the different hydrogen production routes and the transportation system considering the total life cycle (production of FC bus, operation and end of life) along with diesel and natural gas as 'conventional' fuels for bus operation. In addition to the discussion of hydrogen production, aspects of the total life cycle of the transportation system, with main focus on the operation, will be discussed.

3:30 PM *G2.3

Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Emissions. Michael Wang[1] and Norman D. Brinkman[2]; [1]Center for Transportation Research, Argonne National Laboratory, Argonne, Illinois; [2]R&D Center, General Motors, Warren, Michigan.

In comparing future propulsion system options, such as gasoline vehicles, diesel vehicles, ethanol vehicles, hybrids, and hydrogen fuel cells, it is important to consider the energy and emissions used in fuel production and distribution as well as those for vehicle operation. Analyses of the entire vehicle fuel lifecycle are called well-to-wheels analyses. General Motors, Argonne National Laboratory, and others recently completed well-to-wheels analyses of 124 fuel pathway/propulsion system combinations for a 2010 model year truck operating in the year 2016. The work updates previous studies by including emissions of nitrogen oxides, carbon monoxide, volatile organic compounds, particulate matter, and sulfur oxides.
Well-to-tank and well-to-wheels integration were based on Argonne's GREET model. Tank-to-wheels analyses were conducted using a proprietary GM vehicle simulation tool that incorporates powertrain and component performance maps. The results of our well-to-wheels analysis of criteria pollutant emissions show that, as tailpipe emissions from motor vehicles continue to decline, well-to-tank activities could represent an increased share of well-to-wheels emissions, especially for hydrogen, electricity, ethanol, and Fischer-Tropsch diesel. Thus, in order to achieve reductions in criteria pollutant emissions by advanced vehicle technologies, close attention should be paid to emissions from well-to-tank as well as tank-to-wheels activities. We show that energy and environmental benefits of fuel cell vehicles can be guaranteed only by using hydrogen from clean feedstocks and efficient production pathways. In addition, our study separates energy use into total energy, fossil energy, and petroleum energy. Separate results for each of the three energy types shed light on the true energy benefits offered by various transportation fuels, such as corn and cellulose-derived ethanol. We also show that fuel production is a substantial contributor to well-to-wheels energy use and emissions for all pathways except renewable electricity. For example, more than

one-half of well-to-wheels NOx emissions for the baseline gasoline vehicle resulted from gasoline production and distribution. Fuel cell vehicles operating on hydrogen made from natural gas, had about a 50% reduction in well-to-wheels nitrogen oxides compared to the gasoline baseline. On the other hand, for fuel cell vehicles operating on hydrogen made from electrolysis with the U.S. mix of electricity, large increases in both nitrogen oxides and particulate matter were observed relative to the baseline gasoline case. To eliminate emissions and fossil energy use, fuel cell vehicles must be operated on hydrogen generated from renewable electricity.

4:00 PM G2.4

A Life Cycle Analysis of Hydrogen Production for Buildings and Vehicles. Kendra Tupper and Jan F. Kreider; Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, Boulder, Colorado.

Aspects of the hydrogen economy are addressed by quantifying external costs associated with a hydrogen-based energy infrastructure using standard Life Cycle Analysis (LCA) methodology. In addition, methods developed by the ExternE (External Costs of Energy) approach are used to assess the external costs of hydrogen production. We evaluate whether hydrogen should replace other fuels for certain end uses and, if so, how this hydrogen should be produced and used for minimal environment impact and cost. The approach used by ExternE to quantify pollution externalities provides a rational method that can be used as a part of policy decisions. A key step in the ExternE process requires an impact pathway analysis (IPA) tracing the passage of pollutants from emitter (power plant, vehicle) to receptor (population, crops). The ExternE methodology is closely related to LCA because all components of fuel cycles are examined from cradle to grave. While LCA identifies and quantifies all emissions and burdens associated with a process, the IPA of the ExternE methodology enhances LCA analyses by quantifying damage costs. Although uncertainties may increase as the analysis is extended by the additional step of monetarily quantifying impacts, an IPA provides a common basis for economic comparison of all impacts, while an LCA stops short of that. In this study, we use the basic principles of LCA to enhance the completeness and consistency of the IPA. Specifically, the Life Cycle Inventory (LCI) portion of the LCA is in the present work to identify the sources of environmental impacts for the IPA. To perform the LCI, the EcoInvent® database is used with SimaPro 6.1. The LCI results become inputs to RiskPoll (an ExternE tool), which performs a detailed IPA. For example, within RiskPoll, the LCI data are used in dispersion models to determine impacts based on dose-response functions. These impacts are assigned monetary valuation as the final step. Policymakers need to be aware of the true costs associated with an energy economy fueled by hydrogen, rather than trivial first-law calculations that do not address costs or environmental impacts that have been proposed by some. Assigning external costs can help to answer some crucial questions that are currently facing energy policymakers. This paper reports details of answers to these questions: 1. Should hydrogen replace coal, natural gas, and fuel oil as our source for electricity, thermal energy and transportation fuel from LCA and damage cost viewpoints? 2. If so, what is the preferred hydrogen production process of the many proposed? 3. What is the optimal infrastructure for the preferred hydrogen economy in terms of minimizing the negative external impacts on society?

4:15 PM *G2.5

Life Cycle Assessment of Alternative Fuels for Light-Duty Vehicles: Assessing the Potential of Biomass Derived Alternatives. Heather L. MacLean, Sabrina Spatari and Jesse S. Fleming; Civil Engineering, University of Toronto, Toronto, Ontario, Canada.

We evaluate a set of alternative fuels and propulsion systems for the light-duty vehicle (LDV) fleet, focusing on cellulose-derived fuels produced from energy crops, and agricultural and forest residues. Biomass feedstocks can be converted into a number of fuels/energy carriers for use in LDV including; ethanol, hydrogen and Fischer-Tropsch diesel (FTD). Displacing a moderate to large amount of the gasoline currently used in the LDV fleet with a domestically grown, cellulose-derived fuel can make progress towards a "sustainable personal transport sector" since cellulosic fuels are renewable, and their production and use offer low greenhouse gas (GHG) emissions. While these benefits are well known, many gaps in knowledge remain. Life cycle models help determine whether an alternative LDV option has the potential for lower environmental impacts. We compare select publicly available life cycle assessment (LCA) studies of alternative fuels for LDV considering energy use and GHG emissions from cellulose-derived fuels. We highlight the results of the comparison and discuss the challenges of comparing LCA studies (e.g., methodological differences, varying assumptions concerning feedstocks, production processes, and vehicle characteristics, and expectations about process developments). We then detail our development of LCAs of cellulosic fuels that are not considered in the above studies namely, corn stover-derived ethanol, switchgrass derived hydrogen, switchgrass-derived FTD, and municipal solid waste (MSW)-derived ethanol. We compare these new pathways with selected fuel/vehicle pathways in a seminal LCA of alternative fuel/propulsion systems for LDV, the General Motors' "Well-to-Wheels Analysis of Advanced Fuel/Propulsion Systems". The baseline for comparison is the low sulfur reformulated gasoline internal combustion engine vehicle. All of the cellulose (and starch)-based fuel/propulsion systems offer significant WTW fossil energy use and GHG emissions reductions compared to the baseline. The GM corn ethanol pathway is less attractive, and their cellulosic ethanol pathway more attractive, than the pathways developed in this work. For corn ethanol, this is due to it having large fossil energy requirements in production, unlike the cellulosic ethanol. GHG emissions results for the pathways developed in this work are generally similar when compared to the baseline. The exception to this is the MSW to ethanol pathway which has higher WTW GHG emissions than the other cellulosic pathways. This is mainly due to the MSW-ethanol being based on much "nearer-term" technologies than many of the cellulose-based processes, co-product credits (for plastics and lime) are not included in the analysis at this stage, and fossil fuel process energy required for conversion of MSW to ethanol. The cellulosic hydrogen pathway results are more attractive than those for ethanol and FTD due to the assumed use of the former fuel in a more efficient propulsion system (FCV).

SESSION G3: Photovoltaics
Chair: Vasilis Fthenakis
Tuesday Morning, November 29, 2005
Room 303 (Hynes)

8:30 AM *G3.1

LCA-based evaluation of ecological impacts and external costs of current and new electricity and heating systems. Roberto Dones and Thomas Heck; Paul Scherrer Institut, Villigen PSI, Switzerland.

A systematic LCA study of current European electricity and heat systems performed in the frame of the Swiss project ecoinvent was extended to a few new technologies and used as a basis for comparison and ranking using selected LCIA methods and external costs assessment. Besides energy systems, the background LCI database ecoinvent includes transport, building materials, chemicals, metals, paper, waste management and agricultural sectors. The energy systems include full process chains from extraction of resources through waste disposal. The external costs from airborne emissions were estimated using the most recent findings of the ExternE series on the average damage factors for Europe. In general, current fossil electricity systems exhibit the highest LCIA scores, unless non-energy resources are valued high together with low or zero weight on energy resources, as well as the highest external costs, unless greenhouse gas emissions (GHG) are valued very low (sensitivity) and advanced technologies are applied. Alpine hydropower always exhibits the lowest score. Environmental performance of current renewables is generally better than fossil but ranking for wind and PV may significantly worsen when increased importance is attributed to abiotic resource depletion. Wood cogen may have a relatively poor score compared to other renewables. Nuclear shows generally good performance, unless the high radioactive wastes are given subjectively high negative value. Advanced fossil technologies have substantially reduced external costs, with the gas combined cycle performing best, but they are still worse than wind, nuclear and future PV. External costs from wood cogen are comparable to gas cogen or to advanced coal. GHG relative contribution to external costs is high for all fossil technologies, using the base case factor of 19 E/tonne CO2. For heating systems, oil has higher external costs than natural gas, with conventional wood in between. External costs of HP strongly depend on the origin of the electricity supplied. Sensitivity analyses were performed for external costs to reflect uncertainties of impacts and variations in monetary valuation. Alpine hydropower always remains the best performer, followed by wind, whereas fossils stay worst performers. External costs of nuclear remain low, but are comparable to PV when long-term effects of radioactivity are not discounted, in combination with a low damage factor for GHG. Using allocation by exergy, electricity by diesel and natural gas cogen ranks worse than oil and natural gas combined cycle, respectively, and never better than renewables or nuclear. For heating systems external costs, oil always exceeds natural gas systems. Wood systems are the worst performing when GHG is valuated low or local damages are enhanced. With exergy allocation, heat from diesel and natural gas cogen is always ranked better than fossil boilers. Future HPs driven by natural gas or nuclear/renewable electricity always perform best.

9:00 AM *G3.2

The Importance of Balance of System in LCA of Photovoltaic

Systems, Present Status and Future Implications. Paolo Frankl, Ecobilancio Italia, Rome, Italy.

Photovoltaic (PV) systems are energy devices, which directly convert sunlight in electricity. They are constituted by an active part (the PV module) and a set of additional passive components, which are necessary to provide useful energy to the user. The latter include mechanical components (e.g. the mounting structures of the modules) and electrical components (e.g. the inverter). The ensemble of additional components is usually referred to with the term Balance of System (BOS). Most Life Cycle Assessment (LCA) studies on PV systems focus on modules. Rightly so, because the module is the technological heart of a PV system. However, in order to obtain a complete assessment of PV electricity production, which can be compared with other energy sources, BOS cannot be neglected. The objective of the present paper is to assess the importance of BOS in an LCA of present and future PV systems. The relevance of BOS depends on several factors. A first distinction to be made is between centralized systems (ground mounted power plants) and distributed building-integrated systems. In the first case the system simply consists in a PV field, which occupies a large open air surface. As far as integrated building systems are concerned, a great variety of application exist. First of all a distinction to be made is between retrofit installation on existing buildings and integrated systems in new buildings. The second distinction is in function of the used surface (roofs vs. facades). The third classification is between opaque PV cladding (e.g. roofs) and semi-transparent systems (e.g. skylights, facade windows, etc.). The paper presents the results for several PV systems, e.g. ground mounted power plants, retrofit tilted roofs, integrated tilted roofs, integrated facades, skylights and solar tiles. Results are shown for past, present and future PV systems. The paper shows that in the past the share of impacts related to BOS on the whole life cycle of PV systems has been limited. This is mainly due to the high energy consumption in the production of past crystalline silicon modules. However, already today, both crystalline silicon and thin film modules have much lower energy consumption and emissions than in the past. As a consequence, the impacts related to BOS materials are higher in percentage. The paper shows a series of LCA results related to both standard and current state-of-the art BOS solutions. Finally, implications for the future are discussed. It is shown that environmental impacts related to future PV thin film and advanced silicon modules will further decrease. As a consequence, the right choice of BOS materials will be very important in order to guarantee the overall sustainability of PV systems. More attention will have to be focused on the overall PV system design, aiming at the minimization of employed materials and the use of secondary materials for the mounting structures.

9:30 AM G3.3

Life Cycle Greenhouse Gas emissions from the Nuclear and Photovoltaic Fuel Cycle. Vasilis Fthenakis and Hyung Chul Kim; National Photovoltaic EH&S Research Center, Brookhaven National Laboratory, Upton, New York.

Due to the growing concerns regarding the global warming issue, increasing attention is paid to “carbon-free” electricity generation options such as nuclear power and photovoltaic (PV) solar technologies. The life cycle greenhouse gas (GHG) emissions from these technologies are minimal compared with the technologies based on fossil fuel combustion. The life cycle GHG emissions from these technologies, however, are not completely understood at this point. Recent studies show that the nuclear fuel cycle is more benign in terms of GHG emissions than the PV fuel cycle (European Commission, 2003). However, this conclusion is based on outdated data on PV technologies (Fthenakis et al., 2005). In addition, end-of-life nuclear fuel cycle stages, such as the permanent disposal of spent nuclear fuel, are yet to be realized and have not been studied in detail. Furthermore, perhaps due to the difficulties associated with data availability, the range of GHG estimations for the nuclear fuel cycle is very wide (e.g., 3-40 g CO2 eq./kWh), and it may overlap with the range of GHG emissions estimated for the PV solar cycle. It would be essential that, for a fair comparison between these two technologies, the GHG emissions need to be understood under specific technological, regional, and time constraints. This study analyzes the life cycle GHG emissions from the nuclear fuel cycle and the PV fuel cycle specifically in the US context. The most up-to-date thin film technologies, as well as conventional, silicon-based PV modules will be investigated. Thin film PV modules are known to be less energy and material intensive, compared with bulk PV modules. For the nuclear fuel cycle, GHG emissions which are not included in previous studies are discussed. In particular, the GHG emissions associated with the permanent disposal of spent nuclear fuel are estimated based on the engineering plan of the Yucca Mountain project. The GHG emissions from other nuclear fuel cycle stages including mining/milling, fuel conversion, enrichment, fuel fabrication, reactor operation, and construction/decommission are reviewed and updated based on available statistics and literature. This study will also compare well-defined trends in these technologies. In particular, the effect of decreasing availability and grade of raw materials on the life cycle GHG emissions will be discussed. The findings and discussions in this study will contribute to understanding the total external costs associated with electricity usage, which are derived from emission factors as well as risk factors. References 1. Fthenakis, V. M., Alsema, E. A., and de Wild-Scholten, M. J., Life Cycle Assessment of Photovoltaics: Perceptions, Needs, and Challenges, 31st IEEE Photovoltaic Specialists Conference, Jan 3-7, 2005, Orlando, FL. 2. European Commission, Directorate-General for Research (2003): “External Costs. Research results on socio-environmental damages due to electricity and transport”; EUR 20198.

9:45 AM G3.4

Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production. Mariska de Wild-Scholten[1] and Erik Alsema[2]; [1]Solar Energy, Energy Research Centre of the Netherlands, Petten, Netherlands; [2]Copernicus Institute, Utrecht University, Utrecht, Netherlands.

Reliable data on the environmental impacts of PV module manufacturing have been rather scarce for the last 10-15 years. The only extensive data collection based on production data was published in 1992 and was based on technology from the late 80s. Consequently, life cycle assessment and external cost studies were often based on the older data set that does not really reflect the technological progress made over the past decade. Together with 11 European and US photovoltaic companies an extensive effort has been made to collect Life Cycle Inventory (LCI) data that represents the current status of production technology for crystalline silicon modules. This module type was used in about 90% of the 1200 MW of installed PV system capacity installed in 2004. The new data covers all processes from silicon feedstock production to cell and module manufacturing. All commercial wafer technologies are covered, that is multi- and monocrystalline wafers as well as ribbon technology. The presented data should be representative for the technology status in 2004. While the actual results in terms of environmental impacts are presented separately [1] we will focus in this contribution on the process of collecting LCI data Because one of our aims was to prepare a publishable set of LCI data (i.e. data on material and energy inputs, as well as emissions per process step) we tried to get at least three data suppliers for each process step and process technology (e.g. mono vs. multi-Si). In this way we could generate average LCI data without disclosing proprietary information. This goal was realized to a large extent but in some cells of the process/technology matrix the data collection took more time or the process was less well covered so that we had to make use of existing data from literature. Also we needed to aggregate the process data into 4 main process steps. In our presentation we will discuss some of the problems that were encountered during data collection, such as handling confidentiality, data inconsistencies, different system boundaries, aggregation of data, etc. Based on this we will present some guidelines that may be used for comparable projects. For fast dissemination of this information, the LCI data will also be made available on the Internet in the EcoSpold data format. This research was conducted within the Integrated Project CrystalClear and funded by the European Commission. References [1] E.A. Alsema, M.J. de Wild-Scholten, Environmental Impacts of Crystalline Silicon Photovoltaic Module Production, this conference [2] E.A. Alsema, M.J. de Wild-Scholten (2005) The real environmental impacts of crystalline silicon PV modules. An analysis based on up-to-date manufacturers data, 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain [3] EcoInvent2000 Life Cycle Inventory database, http://www.ecoinvent.ch/

10:30 AM *G3.5

Environmental Impact of Crystalline Silicon Photovoltaic Module Production. Erik Alsema[1] and Mariska J. de Wild-Scholten[2]; [1]Science, Technology and Society, Copernicus Institute, Utrecht University, Utrecht, Netherlands; [2]Unit Solar Energy, Energy research Centre of the Netherlands ECN, Petten, Netherlands.

Reliable data on the environmental impact of PV module manufacturing have been rather scarce over the last 10-15 years. The only extensive data collection based on production data was published in 1992 and was based on technology from the late 80s. Consequently, life cycle assessment and external cost studies were often based on the older data set which does not reflect the technological progress made over the past decade. Together with 11 European and US photovoltaic companies an extensive effort has been made to collect Life Cycle Inventory data that represents the current status of production technology for crystalline silicon modules. This module type contributes to about 90% of the 1200 MW of PV system capacity installed in 2004. The new data covers all processes from silicon feedstock production to cell and module manufacturing. All commercial wafer technologies are covered, that is multi- and monocrystalline wafers as well as ribbon technology. The presented data should be considered representative for the technology status in 2004. While the process of collecting Life Cycle Inventory data is presented separately [1] we will focus in this contribution on the actual results in terms of environmental impact. We will present a few representative photovoltaic system applications and consider the relative impacts of PV modules versus other system components, the contribution of electricity input to the overall impact and the key material inputs. Production processes with major impacts will be identified and prospects for future improvements will be analysed. Also areas of uncertainty due to incomplete or contradictory data will be reviewed. Finally we will compare PV system impacts with those of other energy technologies and discuss the CO2 mitigation potential of PV technology for different time horizons. This research was conducted within the Integrated Project CrystalClear and funded by the European Commission. References [1] M.J. de Wild-Scholten, E.A. Alsema, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production, this conference [2] E.A. Alsema, M.J. de Wild-Scholten (2005) The real environmental impacts of crystalline silicon PV modules. An analysis based on up-to-date manufacturers data, 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain

11:00 AM G3.6

Life Cycle Energy Use and Greenhouse Gas Emissions Embedded in Electricity Generated by Thin Film CdTe Photovoltaics. Hyung Chul Kim and Vasilis Fthenakis; National Photovoltaic EH&S Research Center, Brookhaven National Laboratory, Upton, New York.

With a growing public interest in renewable energy sources, significant attention is paid to the life cycle analysis (LCA) of photovoltaic (PV) devices. Thin film CdTe modules are one of the fastest growing PV technologies due to their low production cost. In its early stage of commercialization, the life cycle environmental performance of a CdTe solar cell is relatively unknown compared with silicon based ones. First, the life cycle energy use and emission data on the Cd and Te material production stages are very scarce (Fthenakis and Wang, 2005). In addition, previous energy and emission estimates of the CdTe module production stage need to be updated as advanced vapor deposition processes have prevailed (Fthenakis et al., 2005). The present study investigates the life cycle inventory (LCI) of thin film CdTe PV modules and systems based on PV modules produced by an advanced vapor deposition technology in the US. The raw material production stage of Cd and Te, mostly produced as a byproduct of Zn and Cu smelter respectively, is inextricably linked to the base metal production. The energy use and emissions from the raw material extraction and purification of Cd and Te will be determined on the basis of the allocation rules established by the ISO, along with industry operation data. If possible, energy and emissions associated with synthesizing and compounding the major materials used in the module such as CdTe, CdS, glass, and EVA will be collected from their suppliers. Commercial databases and industry statistics will be also used as a secondary data source if necessary. The LCI of CdTe PV module production stage will be obtained directly from a commercial scale production plant with a 25 MW capacity. Finally, the recycling stage of CdTe PV module will be investigated for a possible future scenario. On the basis of the results, the two important metrics of the PV fuel cycle efficiency, the energy payback time and the greenhouse gas emissions per kWh electricity produced, will be estimated for a commercial PV power plant and for roof top residential applications. The findings and implications of the present study could be used to represent the up-to-date environmental performance of the PV fuel cycle in comparison with other energy technologies. References 1. Fthenakis, V. M. and Wang, W., Life Cycle Inventory Analysis in the Production of Metal Used in Photovoltaics, BNL report, in progress. 2. Fthenakis, V. M., Alsema, E. A., and de Wild-Scholten, M. J., Life Cycle Assessment of Photovoltaics: Perceptions, Needs, and Challenges, 31st IEEE Photovoltaic Specialists Conference, Jan 3-7, 2005, Orlando, FL.

11:15 AM G3.7

Life Cycle Analysis of Solar Module Recycling Process. Karsten Wambach[1], Anja Mueller[1] and Erik Alsema[2]; [1]Deutsche Solar AG, Solar Material, Freiberg, Germany; [2]Department of Science, Technology and Society, Copernicus Institute, Utrecht, Netherlands.

The production and installation of photovoltaic modules in Germany has increased rapidly in recent years. As a result, we will see in the near future – though slightly delayed due the technologies long lifetime – a vast increase in PV modules as waste. For this reason, suitable methods for waste management are currently being investigated. For single- and multi-crystalline solar cells, recovery of the intact cells is a appropriate solution. Life cycle assessments of photovoltaic modules are performed in the past without consideration of the end-of-life phase. This gap is filled by the presented work. The only recycling process for crystalline modules in operation is the process of Deutsche Solar. Hence the main focus of the work is set to this process. The intention of the study is to scrutinise if the process is benificial compared to other end-of-life scenarios concerning environmental aspects. Alternative end-of-life scenarios are low grade solutions like a shredder process with subsequent material sorting or thermal waste treatment in a municipal incineration plant as well as the disposal on a landfill. In Freiberg Deutsche Solar is carrying out a process which enables to recover the solar wafers of crystalline modules. By burning off the laminate solar cells are firstly removed out of the module compound structure. Following the metallization, anti-reflection coating and pn-junction of the cell are removed in an etching line. The final product of the recycling process can be processed again and integrated in a new PV module. In the presented LCA study the emissions, energy and material streams of the thermal and chemical treatment are considered. It will be shown that recycling of crystalline silicon PV modules by the considered process has clear environmental benefits, mainly because of the possibility to reuse the wafers. Furthermore the energy pay back time of a module with recycled cells is substantially lower than of a module with new cells.

SESSION G4/S4: Joint Session: Nanomaterials: Biological and Environmental Interactions

Chair: Vicki Stone
Tuesday Afternoon, November 29, 2005
Room 203 (Hynes)

1:30 PM *G4.1/S4.1

Toxicological Profiles of Nanomaterials. Erik Rushton, Gunter Oberdorster and Jacob Finkelstein; University of Rochester, Rochester, New York.

With the passage of the National Nanoscale Initiative in 2001 there has been increasing attention and funding given to nanomaterial research. This has led to a number of new materials developed at the nanoscale (< 100 nm) level, which often possess chemical and physical properties distinct from those of their bulk materials. These unique qualities are proving to be quite useful in a number of new applications. For example, biological applications in imaging, treatment, and drug delivery are particularly promising as well as the increasing engineering potential of nanocircuitry and materials science. As the number of applications increases however, so too does the potential for human exposure to nanomaterials through a number of routes: dermal, ingestion, inhalation, and even injection. Interestingly some of the properties of these nanomaterials that make them useful in these emerging technologies are the same properties that can increase their toxic potential. This is leading to an emerging discipline - nanotoxicology, which can be defined as safety evaluation of engineered nanostructures and nanodevices. Nanotoxicology research will not only provide information for risk assessment of nanomaterials based on data for hazard identification, dose response relationships and biokinetics, but will also help to further advance the field of nanoresearch by providing information to alter undesirable nanomaterials properties. Although nanotoxicology is in its infancy, there are some preliminary studies with newly developed materials that provide some insight into potential effects, which when coupled with older studies provides some insight on how these nanomaterials impact the biological system. This presentation summarizes results of studies with nanosized particles with a focus on the respiratory system and skin as portals of entry. The ability of particles to translocate from their site of entry, their ability to elicit biological responses, and their presumed mechanisms of action will be highlighted. This will be an attempt to illustrate how pervasive these materials can be, which may or may not be detrimental. With proper toxicological assessment this potential may be harnessed leading to breakthroughs at the nanotechnology - biology interface.

2:00 PM *G4.2/S4.2

Pulmonary Effects in Rats of Exposure to Nanoscale Titanium Dioxide or Nanoscale Quartz Particles: Particle Size and Surface Area are not the Only Considerations. David B. Warheit[1], Kenneth L. Reed[1], Thomas R. Webb[1], Christie M. Sayes[2] and Vicki L. Colvin[2]; [1]DuPont Haskell Laboratory, Newark, Delaware; [2]Rice University, Houston, Texas.

Numerous pulmonary toxicology studies in rats have demonstrated that nanoscale particles (generally defined as particles in the size range < 100 nm) administered to the lung cause a greater inflammatory response when compared to fine-sized particles of identical composition at equivalent mass concentrations. Contributing to the effects of nanoscale particles is their very high size-specific deposition when inhaled as singlet ultrafine particles rather than as aggregated particles. Some evidence suggests that inhaled nanoparticles, after deposition in the lung, largely escape alveolar macrophage surveillance and clearance and gain access through translocation to the pulmonary interstitium. In addition, in vitro studies suggest that nanoparticle-types are more toxic to pulmonary cells. However, some recent preliminary studies indicate that pulmonary exposures to nanoscale particulates may not always be more inflammogenic compared to macro/microscale particles. Indeed, data will be presented demonstrating that nanoscale quartz-crystalline silica particles (50 nm particle size) were less toxic to the lungs when compared to fine-sized quartz particles (1.6 um). However, when these studies were repeated with 10 nm quartz particles, the nanoscale quartz particles were as or more toxic than Min-U-Sil quartz. In another study, lung toxicity of intratracheally instilled Nano titania particles were compared to fine-sized particulates in rats. The effects of nanoscale TiO2 rods as well as Nano TiO2 dots (20 nm) were not significantly different from larger sized TiO2 particles (300 nm) at equivalent doses and this finding was confirmed in a second study. In another study with surface treatments on TiO2 particle-types, results demonstrated that surface coatings can modify the pulmonary toxicity of particles. In the aggregate, these studies indicate that a variety of factors beyond particle size and surface area serve to influence the pulmonary toxicity of nanoparticulates.

3:30 PM *G4.3/S4.3

Suggested Strategies for the Ecotoxicology Testing of New Nanomaterials. Vicki Stone, A. Ford and T. Fernandes; School of Life Sciences, Napier University, Edinburgh, United Kingdom.

Nanotechnology is a rapidly expanding and advancing field of research that has already yielded a variety of commercially available products including cosmetics, suntan lotions, paints, self cleaning windows and stain resistant clothing. The Royal Society and the Royal Academy of Engineering in their recent report 'Nanotechnology and nanoscience: opportunities and uncertainties' (http://www.nanotec.org.uk/finalReport.htm) concluded that nanotechnology is likely to have 'huge potential'. While this report indicated that 'many applications of nanotechnology pose no new health or safety risks', it also recognised that the health, safety and environmental hazards of nanoparticles (diameter less than 100nm) and nanotubes requires investigation. A significant body of data exists regarding the toxicological effects of nanoparticles (also termed ultrafine particles) in mammalian systems, particularly with respect to the lungs and cardiovascular system. Such studies suggest that smaller particles, with a larger surface area per unit mass, are more potent at inducing oxidative stress and inflammation leading to adverse health effects. However, very few papers have been published regarding the effects of nanoparticles on other phyla such as micro-organisms, invertebrates and vertebrates from terrestrial and aquatic habitats. Since nanoparticles from both domestic and industrial products will be released into the environment, eg. wastewater, it is essential to investigate the impact on such species and the ecosystem. This presentation will aim to discuss how existing knowledge regarding the mammalian toxicology of nanoparticles could be used to generate an effective, efficient and focused strategy for testing the ecotoxicolgy of nanoparticles.

4:00 PM *G4.4/S4.4

Case Studies for Environmentally-Conscious Materials Selection with the CES Eco-Selector. Ulrike G.K. Wegst[1] and Michael F. Ashby[2]; [1]Max-Planck-Institute for Metals Research, Stuttgart, Germany; [2]Cambridge University Engineering Department, Cambridge, United Kingdom.

Materials contribute to the environmental burden of products during all stages of their life-cycle: their creation, use and disposal. The minimisation of this burden requires the selection of materials which are less toxic, can give products which – without compromising product quality – have a longer life-time, are more easily recycled, are lighter and less energy intensive, and which, where possible, use renewable or non-critical resources. Presented in this contribution are case studies on material substitution for lightweight cars and high performance sports equipment to illustrate how the Cambridge Eco-Selector, a software-based design tool, can aid the environmentally-conscious selection of materials. It is unique in that it provides guidance in the design of new and improved products early in the "concept" and "embodiment" stages of the design process, allowing for the simultaneous optimisation of technical, environmental and cost performance.

4:30 PM G4.5/S4.5

Atomic force microscopy of CHO cells exposed to quantum dots. Minhua Zhao[1], Charudharshini Srinivasan[2], Jeunghoon Lee[1], Diane Burgess[2], Fotios Papadimitrakopoulos[1] and Bryan D. Huey[1]; [1]Institute of Materials Science, University of Connecticut, Storrs, Connecticut; [2]School of Pharmacy, University of Connecticut, Storrs, Connecticut.

Atomic force microscopy (AFM) can be uniquely employed for dynamic nano-indention to probe the viscoelastic material properties of living cells in culture. AFM elastography, which maps the spatial distribution of cell mechanical properties with nanoscale resolution, has been used to investigate a living CHO (Chinese Hamster Ovary) cell culture. Quantum dots (QDs) are able to cross the cell membrane and to act as a fluorescent label. In this work, AFM elastography is captured on living CHO cells before and after introducing CdSe QDs into the cultural media. The accumulation of QDs within the cell is confirmed by in situ epifluorescence equipped on the AFM. AFM elastography before and after the addition of QDs at various concentrations is reported.

4:45 PM G4.6/S4.6

Characterization, Imaging and Degradation Studies of Quantum Dots in Aquatic Organisms. Kenneth E. Gonsalves[1], Sireesha Khambhammettu[1] and Amy H. Ringwood[2]; [1]Chemistry, University of North Carolina at Charlotte, Charlotte, North Carolina; [2]Biology, University of North Carolina at Charlotte, Charlotte, North Carolina.

Nanoparticles may be introduced into aquatic environments during production processes and also as a result of release following their use in electronic and biological applications. The purpose of these studies was to characterize and image the behavior of quantum dots (QD) in seawater, and the accumulation of QDs and their toxicity to potential biological receptors. For these studies, oyster embryos as well as isolated hepatopancreatic cells were used. Fluorescent confocal microscopy, electron diffraction and electron microscopy were used to determine the size distribution and composition of quantum dots and also to verify the accumulation and cellular localization inside these cells. Furthermore, there are natural differences in environmental factors that may affect the degradation rates of QDs, including salinity and pH conditions, as well as seasonal differences in temperature. To determine the effects of salinity on degradation rates, nonfunctionalized QDs composed of a Cd/Se core surrounded by layers of Zn (Evident Technologies) were added to 0.22 filtered seawater samples of different salinities (10, 20, and 30 parts per thousand), and the changes in emission spectra over time were determined; likewise, the potential effects of pH were evaluated under a range of environmentally realistic pH conditions (e.g. pH 7, 7.5, and 8); and the impacts of temperature (10, 20, and 30 degrees centigrade) were determined. These kinds of basic studies are essential for addressing the potential impacts of nanoengineered particles on aquatic organisms. Analogous studies with InP nanoparticles will also be presented.

SESSION G5: Global Warming and End-of-Life Case Studies

Chair: Stella Papasavva
Wednesday Morning, November 30, 2005
Room 303 (Hynes)

8:30 AM G5.1

The Effect of Emissions from Fossil Fuel Combustion on Global Climate Change. Kristy E. Ross[1,2] and Stuart J. Piketh[1]; [1]Climatology Research Group, University of the Witwatersrand, Johannesburg, South Africa; [2]Eskom TSI, Johannesburg, South Africa.

Emissions from fossil fuel combustion alter the composition of the atmosphere and have been touted as a major cause of climate change. Global warming is thought to occur due to the increased concentration of greenhouse gases which enhance the absorption and emission of infrared radiation by the atmosphere. Combustion also produces aerosol particles, which either increase the scattering of incoming solar radiation back to space, resulting in an increase in planetary albedo, or absorb solar radiation directly, leading to local heating of the atmosphere. The climate system must respond to these changes in radiative forcing in order to restore the energy balance. Average global surface temperature has increased by approximately 0.6°C since pre-industrial times. The warming is far from uniform, however, and often manifests itself as an increase in climatic extremes. The difficulty in attributing the observed climate change to human activities lies in the fact that the anthropogenically-induced warming is superimposed on natural climatic variability. Paleoclimatic records dispel the myth of a static climate – ocean core sediments show a regular oscillation, on a 100 000-year cycle, between glacials and interglacials. Superimposed on these long-term oscillations are shorter scale variations. While long-term climatic changes appear to be related to changes in the amount of solar radiation received by the earth due to changes in the earth's orbit around the sun, shorter term variations are mainly related to feedbacks within the earth-atmosphere system. A firm link between atmospheric composition and temperature has been established from ice core records spanning the last 400 000 years, which show that fluctuations in global temperature and atmospheric concentrations of carbon dioxide and methane are tightly coupled. The range over which temperature and trace gas concentrations vary is bounded at upper and lower limits, which have been exceeded by current CO_2 levels. The detection and attribution of anthropogenic climate change and predictions of future change will be discussed.

8:45 AM G5.2
The Global Warming Effect of Dams Decommissioning: A Life Cycle Perspective. Sergio Pacca, Center for Sustainable Systems, University of Michigan, Ann Arbor, Michigan.

Greenhouse gas (GHG) emissions from hydroelectric dams are often portrayed as nonexistent by the hydropower industry and have been largely ignored in global comparisons of different sources of electricity. However, the life cycle assessment (LCA) of any hydroelectric plant shows that GHG emissions occur at different phases of the power plant life. This work examines the role of decommissioning hydroelectric dams in greenhouse gas emissions. Accumulated sediments in reservoirs contain noticeable levels of carbon, which may be released to the environment upon decommissioning of the dam. I surveyed the rate of sediment accumulation and the sediment volume for six of the 10 largest United States hydroelectric power plants. I estimated the amount of sediments and the respective carbon content at the moment of the dam decommissioning (100 years). The released carbon is partitioned into CO2 and CH4 emissions and converted to CO2 equivalent emissions using the global warming potential (GWP) method. The global warming effect (GWE) due to decommissioning the reservoirs is normalized to the total electricity produced over the lifetime of each power plant. The estimated GWE of the power plants range from 233 g of CO2eq./kWh to 690 g of CO2eq./kWh when 11% of the total available sediment organic carbon (SOC) is mineralized and between 63 and 188 g of CO2eq./kWh when 3% of the total SOC is mineralized. These values are on the same order of magnitude of emission factors for coal power plants, which demonstrates that the amount of greenhouse gases emitted by the sediments upon dam decommissioning is a notable amount that should not be ignored and must be taken into account when considering construction and relicensing of hydroelectric dams.

9:00 AM *G5.3
Grand Challenge of Vehicular Hydrogen Storage: Developing an Appropriate Adsorption System. Anne C. Dillon, Y. Zhao, J. L. Blackburn, P. A. Parilla, Y.-H. Kim, S. B. Zhang, C. Curtis, T. Gennett, J. L. Alleman, K. M. Jones and M. J. Heben; Basic Science Department, National Renewable Energy Laboratory, Golden, Colorado.

The United States Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy and the Office of Basic Sciences have concluded that hydrogen storage is a cornerstone technology for implementing a hydrogen energy economy. However, significant scientific advancement is still required if a viable on-board storage technology is to be developed. For example, an adsorption process for on-board vehicular storage will require a hydrogen binding energy between $\sim$20-50 kJ/mol to allow for near-room temperature operation at reasonable pressures. A moderate binding energy is also crucial for managing the heat load during refueling. Typically, non-dissociative physisorption due purely to van der Waals forces involves a binding energy of only $\sim$ 4 kJ/mol, whereas a chemical bond is $\sim$ 400 kJ/mol. The desired binding energy range for vehicular hydrogen storage therefore dictates that molecular H_2 be stabilized in an unusual manor. Thus it seems likely that it is necessary to develop a new class of compounds. Recent theoretical studies[1] have shown that scandium will complex with the twelve five-membered rings in C_{60}. Here the scandium shares charge with all of the carbon atoms in the pentagon through a Dewar coordination. The scandium will then coordinate with five H_2 ligands. One of the hydrogen ligands dissociates and has a binding energy outside the acceptable range for vehicular hydrogen storage. However, the other four hydrogen ligands are stabilized in a molecular (dihydrogen) form with a binding energy of $\sim$ 30 kJ/mol. The reversible hydrogen capacity of this $C_{60}[ScH_2(H_2)_4]_{12}$ system is then 7.01 wt%. Furthermore, it has been predicted that doping a C_{60} fullerene with a boron atom in each of the pentagon rings results in the formation of twelve holes in the electronic structure and the subsequent attachment of a monohydride species to each of the twelve scandium atoms. It is then possible to stabilize five H_2 molecules as dihydrogen ligands with a binding energy of $\sim$30 kJ/mol. The resulting $C_{48}B_{12}[ScH(H_2)_5]_{12}$ has a reversible hydrogen capacity of 8.77 wt.%. The prediction of this novel class of materials as well as rational routes towards their synthesis will be discussed. [1] Zhao, Y.; Kim, Y.-H.; Dillon, A. C.; Heben, M. J.; Zhang, S. B. *Phys.Rev.Lett.* **2005**, *94*, 155504-155501-155504.

9:30 AM *G5.4
A Life Cycle Model to Assess End of Life Vehicle Treatment Options. Candace Sue Wheeler[1,2], Nakia L. Simon[3,2], Claudia M. Duranceau[4,2] and Gerald R. Winslow[5,2]; [1]Chemical and Environmental Sciences Laboratory, General Motors, Warren, Michigan; [2]Vehicle Recycling Partnership, USCAR, Southfield, Michigan; [3]DaimlerChrysler, Auburn Hills, Michigan; [4]Ford Motor Company, Dearborn, Michigan; [5]KBS Consulting, Auburn Hills, Michigan.

Each year in the United States, approximately 15 million automobiles reach the end of their useful life. Over 95% of these end of life vehicles (ELV) enter a complex infrastructure designed to recover materials of value (primarily the ferrous and non-ferrous metals), and the remaining material referred to as shredder residue (SR) or fluff is sent to landfills for disposal. More than 75% of the materials from ELVs are profitably recovered and recycled by the private sector. However, due to increasing environmental awareness, limited landfill space, and the proliferation of environmentally driven regulations, ELV treatment options are becoming more important. While ELV treatment and the subsequent recycling of the recovered materials are important as overall goals, it is also important to know what the effects of the various treatments and recycling processes have in terms of environmental impacts and/or benefits from a global and local perspective. Therefore, an environmental analysis of the various ELV treatment options is essential. One important tool for evaluating ELV processes is life cycle assessment (LCA). The Vehicle Recycling Partnership (VRP) of USCAR (United States Council on Automotive Research) is evaluating various separation and recycling technologies for SR. In order to have a better understanding of the environmental benefits offered by these technologies, the VRP is currently developing a life cycle model of the entire end of life process to map the different options for treating and recycling SR. Life cycle assessment methods will then be applied to the LCI model to determine tradeoffs between alternative technologies and to identify preferred alternatives.

10:30 AM G5.5
Grinding and Separation of The Cellular Phone Housing. Woo-Hyuk Jung[1,2], Nathan Tortorella[2], Charles L. Beatty[2] and Stephen P. McCarthy[1]; [1]Plastics Engineering Department, University of Massachusetts Lowell, Lowell, Massachusetts; [2]Materials Science and Engineering Department, University of Florida, Gainesville, Florida.

The front cover of the Motorola cellular phone housing, which was composed of 62.2 wt% of polycarbonate (PC) /acrylonitrile-butadiene-styrene (ABS), was ground and separated from the undesired materials using sink-float method. The sink-float methods in water and salt were used to remove the floating materials such as the adhesive strips and the foam, and to separate the metal parts where the recovery ratios were 92.8 and 40.5 % in water and salt. The separation of the residual wire and the button rubber, which could not be separated from the sink-float process in water, was preformed using V-Stat Triboelectric Separator (Outokumpu Technology) of the roll separator that also provided the selected method to separate the ground metal existing in the printed circuit board where the recovery weight ratio of metal part was 19 wt%. The separated PC/ABS could be compounded with the ground circuit board or the thermoplastic elastomer called Engage?, or the reactive species of glycidyl methacrylate (GMA).

10:45 AM G5.6
Preparation of Recycled Polycarbonate/Acrylonitrile-Butadiene-Styrene Composites. Woo-Hyuk Jung[1,2], Nathan Tortorella[2], Charles L. Beatty[2] and Stephen P. McCarthy[1]; [1]Plastics Engineering Department, University of Massachusetts Lowell, Lowell, Massachusetts; [2]Materials Science and Engineering Department, University of Florida, Gainesville, Florida.

The front cover of the Motorola cellular phone housing was ground to be as the same size as the original particles prior to use, using the knife mill. The mixture contained 15.2 wt% metal, 1.9 wt% foams, 1.4 wt% rubber and 81.4 wt% thermoplastics (called all housing) where the major component was PC/ABS blends. The separation of the thermoplastic scraps was performed using the sink-float process in water and salt. The impact modification of all housing containing six thermoplastic parts was carried out by the addition of the polyolefin elastomer related to the functionalized polyethylene (PE). The unprinted glass fiber reinforced epoxy circuit boards were size reduced and pulverized using the knife mill and hammer mill. The ground epoxy circuit board was then classified with a set of testing sieves using Gyro sifter and their mean diameters were calculated by means of particle size distribution analysis. Izod impact strength at various temperatures, tensile test, SEM on the fracture surface, and dynamic mechanical spectroscopy were performed to characterize the alloys and mixtures compounded by the batch mixer and the twin screw extruder.

11:00 AM G5.7
Life Cycle Assessment (LCA) and Biodegradability of Biobased Composites. Salil Arora[1], Satish Joshi[3,1], Manjusri

Misra[1], Amar K. Mohanty[2,1] and Lawrence T. Drzal[1]; [1]Composite Materials and Structures Center, Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, Michigan; [2]School of Packaging, Michigan State University, East Lansing, Michigan; [3]Department of Agricultural Economics, Michigan State University, East Lansing, Michigan.

In the current scenario of depleting crude oil resources, many initiatives are undertaken by governments to reduce the reliance on non-renewables and favor the use of biobased products. A recent legislation by United States government under the Farm Security and Rural Investment Act of 2002 (FSRIA) approved guidelines for designating biobased products for federal procurement preference. In this, National Science Foundation (NSF)-funded project, novel biobased composites (polyhydroxybutyrate and natural fibers) were developed at the Composite Materials and Structures Center (CMSC), as alternatives to petroleum-based composites for use in automotive industry. The sustainability of these biobased composites was evaluated using the concept of Life Cycle Assessment (LCA). Comparative Life cycle inventory and impact assessment of polyhydroxybutyrate (PHB)-kenaf and polypropylene (PP)-glass composites shows significant reduction in energy consumption and emissions for the bio-based PHB-kenaf composite. In addition, the biodegradability of these composites under controlled composting environment was assessed based on ASTM D5338. The study was carried out for more than two months, in which biobased composites degraded substantially, evident from quantitative evaluation of carbon dioxide emissions, as well as from the visual inspection of the composite samples. LCA results in combination with biodegradability assessment, confirm the sustainability of biobased composites. Acknowledgments: Financial support for this research was provided by NSF-PREMISE-2002 Award No: DMI 225925.

SESSION G6: LCA Tools and Case Studies
Chair: Vasilis Fthenakis
Wednesday Afternoon, November 30, 2005
Room 303 (Hynes)

1:30 PM *G6.1

Guiding the design and application of new materials for enhancing sustainability performance. Gregory A. Keoleian[1], Alissa Kendall[1], Michael D. Lepech[2] and Victor C. Li[2]; [1]Center for Sustainable Systems, University of Michigan, Ann Arbor, Michigan; [2]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan.

This paper presents a framework for guiding the design of new materials to enhance the sustainability of systems that utilize these materials throughout their production, use and retirement. Traditionally, materials engineering has focused on the interplay between material microstructure, physical properties, processing, and performance. Environmental impacts related to the system's life cycle are not well integrated into the materials engineering process. To address this shortcoming, a new methodology has been developed that incorporates social, economic, and environmental indicators - the three dimensions of sustainability. The proposed framework accomplishes this task and provides a critical tool for use across a broad class of materials and applications. Material properties strongly shape and control sustainability performance throughout each life cycle stage including materials production, manufacturing, use and end-of-life management. Key material parameters that influence life cycle energy, emissions, and costs are highlighted. The proposed framework is demonstrated in the design of engineered cementitious composites, which are being developed for civil infrastructure applications including bridges, roads, pipe and buildings. This research is part of an NSF MUSES (Materials Use: Science, Engineering and Society) Biocomplexity project on sustainable concrete infrastructure materials and systems (http://sci.umich.edu).

2:00 PM G6.2

Strength life cycle analysis of mortars and its environmental impact. Antonia Moropoulou[1], Christopher Koroneos[2], Maria Karoglou[1], Eleni Aggelakopoulou[1] and Kyriakos Labropoulos[1]; [1]School of Chemical Engineering, National Technical University of Athens, Athens, Greece; [2]Laboratory of Heat Transfer and Environmental Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece.

Greece is a country with many old and ancient buildings. All these structures need restoration, and in many cases this becomes very urgent. The materials that are used play the most significant role in all aspects of the structure existence. Aesthetics and durability are the properties that need to be taken into consideration. Both of these properties are affected by time. The proper material would greatly enhance their appearance and their strength. The environmental dimension of these materials may sometimes be a prohibitive factor in the selection of these material. Life Cycle Assessment (LCA) is a tool that can be used to assess the not only the environmental impact of the materials, but also the change of their durability with time. LCA can be a very useful tool in the decision making for the selection of appropriate restoration structural material. In this work, a comparison between traditional type of mortars and more modern ones (cement-based) is attempted. Three mortars of traditional type are investigated: with aerial lime binder, with aerial lime and natural pozzolanic additive, and with aerial lime and artificial pozzolanic additive. The LCA results indicate that traditional mortars are more sustainable compared to cement-based mortars.

2:15 PM G6.3

Life cycle assessment of softdrink delivery systems. Dario Martino[1], Amar Mohanty[1], Susan Selke[1] and Satish Joshi[2]; [1]School of Packaging, Michigan State University, East Lansing, Michigan; [2]Department of Agricultural Economics, Michigan State University, East Lansing, Michigan.

A life cycle assessment was conducted to evaluate the environmental performance of a generic hypothetical carbonated softdrink product, and was used to compare two material alternatives and container sizes, which are: (1) a 16 fl. oz. polyethylene terephthalate (PET) bottle and (2) a 12 oz. aluminum can. The life cycle analysis of the different product delivery systems (PDS) included material production, manufacturing and disposition for primary and distribution packaging, as well as the related transportation links between these stages and filling, retail and the point of consumption. The environmental performance of these systems were evaluated and their impacts on the total life cycle burden were analyzed under different scenarios. Preliminary results show that the aluminum can with 50% recycled content and an US average end-of-life scenario of 50% recycling rate, 49% landfilling has a life cycle energy consumption of about 7850 MJ/1000 l of soft drink delivered to the market. Life cycle energy consumption of aluminum can ranges from 4460 to 11200 MJ/1000 l of delivered product with 100% and 0% recycled content. Virgin PET bottle with 36% recycling and 52% landfilling rates consumes about 8300 MJ/1000 l of soft drink delivered. The life cycle profile of this container type showed that as more components are included in the analysis (i.e. PP caps, LDPE sleeves and carrier ring) the energy consumption increases from 7417 MJ to 8300 MJ/1000 l of soft drink delivered. Further scenarios and a similar analysis on an PLA bottle are assessed and will be included in a final presentation.

3:30 PM G6.4

Development of an Efficient LCA Communication Tool for DfE. Harald Florin[1], Michael Betz[1], Thorsten Volz[1] and Nuno da Silva[2]; [1]PE Europe GmbH, Leinfelden-Echterdingen, Germany; [2]Unilever, Colworth, United Kingdom.

A key element of environmental management in Unilever is Life Cycle Assessment. In such diversified and large company, each decision-maker has a defined area of responsibility, such as packaging innovation and new product formulations. To integrate environmental aspects in decision-making, Unilever managers need decision support in their language and prompt answers to design questions. While the questions asked by stakeholders can be very specific, to answer them, the environmental expert has to develop a holistic model covering all aspects of the life cycle, and communicate a targeted view of the results. This targeted view is usually static and applicable only for a specific case, however, the underlying model would allow the generation of results for design changes without much added work. Currently, only the environmental specialist can generate reports, even if the design changes are within the boundaries of the LCA model. To answer the stakeholders needs and simplify the communication of LCA results, Unilever and PE Europe GmbH have jointly developed an extension tool to GaBi 4 LCA software: GaBi interactive reporting interface (GaBi I-reports). By retaining the model parameters (set by the expert), a specific decision-maker can explore the design brief and generate specific reports. It delivers a transparent view on the product under consideration and creates an immediate environmental dimension on design questions. It need no extra knowledge and no extra training for handling and is adaptable to the complexity of the design questions and motivation of the stakeholders. This solution allows the predefinition of report templates which make use of all available content of a balance analysis such as graphs and tables, pictures of the systems, etc. Structuring elements and free text can be added. By changing the parameters, the stakeholder can define different cases and gets 'just in time' LCA results within his system. This functionality reduces the complexity of large LCA models to just a few aspects that are really interesting to a target group. Compared to written reports the interactive version provides more flexibility in changing variable parameters and direct feedback. In addition, electronic report on LCA is interactive, living and attractive. The report can be applied by anyone and addresses predefined questions on complex systems in a simple and understandable way. This substantially enhances the integration of life cycle considerations in

Unilever's decision making. GaBi I-reports have been developed in 2005. A small case study will be used to illustrate the benefits and the potential applications of this interactive interface.

3:45 PM G6.5

A Hybrid Environmental Life Cycle Assessment of a CMOS Device. Sarah B. Boyd[1,2], Nikhil Krishnan[3,1,2] and Sebastien Raoux[2]; [1]Mechanical Engineering, University of California, Berkeley, Berekeley, California; [2]Capital Assets Management, Applied Materials, Santa Clara, California; [3]Earth Institute, Columbia University, New York, New York.

With rapid growth in the electronics and computer sectors, environmental and health issues associated with semiconductor manufacturing are growing in importance. In addition to environmental impacts during the actual manufacturing process itself, semiconductor manufacturing also mobilizes materials and energy in other industries throughout the economy. To evaluate total environmental impacts associated with semiconductor manufacturing, it is therefore necessary to evaluate impacts in detail within the fab as well as those associated with the entire supply chain, goals suited to hybrid Life Cycle Assessment (LCA). In this work we develop a hybrid model for evaluation of semiconductor life cycle environmental impacts and present LCA results for a current-technology 300mm copper CMOS device. The model uses (i) bottom-up process inventories for semiconductor manufacturing steps and for specialty chemicals materials (e.g. silicon wafers) and (ii) the economic input-output method for chemicals and generic facility inputs (energy, water, gases). Oxidation, deposition, etch, ion implant, electrochemical plating, wafer cleaning, chemical mechanical planarization and lithography are modeled at the equipment level. The functional unit is a generic logic processor. Results are presented in terms of total global warming impact, hazardous emissions, criteria air emissions and volatile organic emissions, as well as energy, water and total material use. For the purposes of this work, four key manufacturing modules are identified: Shallow Trench Isolation (STI), gate stack, via and interconnect, each consisting of numerous individual process steps performed on different equipment sets. We organize facility mass/flow data according to process and equipment sets to construct a library of environmental process models. This approach allows us to analyze different recipe data, emissions data and facility infrastructure options (pumps, abatement devices, HVAC systems, etc.) for each process step. Such a hierarchical organization of data offers three advantages: (i) It allows a separation of proprietary information (from recipes, for instance) from non-proprietary, generic process tools (such as facilities infrastructure), or shared information among companies and (ii) It separates databases that change rapidly (such as recipe databases or platform models) from facility infrastructure data and models that may change less rapidly and (iii) the data collected and models developed may be used (to the extent possible) in inventory analysis of different product types. Economic input-output analysis is performed for energy, water and chemicals. The EIO-LCA portion of the analysis reveals comparable burdens among suppliers to the semiconductor sector. The combination of hierarchical, process-based life cycle inventory and EIO-LCA analysis presents a complete picture of environmental burdens associated with the creation of a single logic chip.

4:00 PM G6.6

Practical LCA for Small and Medium-Sized Enterprises. Lise Laurin[1,2], Gregory A. Norris[2] and Mark Goedkoop[3]; [1]EarthShift, Eliot, Maine; [2]Sylvatica, North Berwick, Maine; [3]PRe Consultants, Amersfoort, Netherlands.

Small and medium sized businesses have traditionally found the finances and time required to perform an LCA prohibitive. At the same time, their customers, often large multinational corporations, are demanding both accountability and improved performance in environmental impacts. A new concept in LCA that allows specialists in things other than LCA to rapidly create both a model and generate "what-if" scenarios will allow even small and medium-sized enterprises (SMEs) to take advantage of the benefits of LCA. These industry-specific "wizards" are built around a manufacturing process and can be rapidly updated or customized to a particular manufacturer or process type. Results can be used internally for decision-making and can also enable manufacturers submit information for environmentally preferable purchasing, eco-labels, and so-on. The issues with LCA for SMEs are as follows: 1. LCA is complex. Educating a manufacturing expert in LCA or an LCA expert in the manufacturing process requires time and money. 2. Significant amount of effort is required to gather the input data . 3. The time and/or cost to generate the LCA model is extensive, whether done in house or done externally. 4. Once completed, most LCA projects cannot be compared for preferred purchasing programs because different assumptions have been made. A new methodology uses automated tools to address the issues To address these issues in the building industry, a methodology was developed around automated software tools with built in "rules" to ensure consistency in data quality as well as consistency in assumptions. The same methodology applies to other industries. The methodology starts by addressing the issue of expertise. The automation, or wizard, is built around the manufacturing process, with default data wherever it is available. Development of the wizard requires education of an LCA expert on the manufacturing process, but this education only needs to happen once for a multitude of products. Once the wizard is developed, the user can create life cycle models for endless products or potential products without having to know much about LCA. Since wizards are modular, complex manufacturing processes with multiple options can be created. Much of the data gathering also occurs during the wizard creation. Default flows (typical materials, energy, and emissions for a particular part of the process) are identified wherever possible, allowing the user to select the defaults or to enter more detailed information whenever they have it. This not only simplifies data gathering, it also simplifies the data entry process for the user. Once completed, the wizard allows a user to rapidly generate a new LCA model. The model can be saved and then modified for comparison. This feature is helpful to compare similar products, to test sensitivity to a particular flow, or to assess the impact of a process or material change.