An Engineering Curriculum Track for IT for Sustainability

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***Abstract*—Information technology (IT) forms a crucial foundation for designing, building and managing future sustainable cities. This paper proposes a model to innovate the engineering and computing curriculum to include sustainability and IT topics in order to develop the skills and competencies that future professionals will need to design, build and manage future cities. Rather than developing a new program, we propose a curriculum model – called SustainIT - adapted from the successful 2006 US NAE Gordon Prize engineering curriculum innovation, The Learning Factory - as a possible roadmap to reform and complement existing Bachelors of Science (BS) degrees in engineering. By providing a series of guided electives, any engineering program may offer engineering, and/or computer science students the opportunity to learn about and become specialized in IT for Sustainability. Multidisciplinary topics include traditional ecological engineering; life-cycle design; design and application of resource microgrids; pervasive sensing and data aggregation; knowledge discovery, data mining and visualization; and, policy based control and operation for resource provisioning.**

Keywords - curriculum innovation, engineering education, BS, sustainability, information technology (IT), future cities.

I. Introduction

A. Motivation

Environmental sustainability is top-of-mind for many university faculty and administrators today, as well as for countries, industry and citizens. Growing concern, both in the developed and developing world, regarding the impact of resource consumption challenges stems from various drivers. The world's population is expected to reach 9 billion by 2050 [1]. How do we deal with the increasing strain that the economic growth is placing on our dwindling natural resources? Can we expect to meet the needs of society by solely relying on replicating and extending the existing physical infrastructure to cope with economic and population growth? Indeed, anecdotal evidence of the strain that society is placing on the supply side—the resources used for goods and services—is apparent: rising prices for critical materials, such as copper and steel; the dramatic reduction in petroleum output around the world; and limitations in city scale waste disposal. Increasing costs for basic resources required for population growth and social services will have a negative impact on economic growth in many geographies. Furthermore, externalities such as environmental pollution, natural disasters and military conflicts are increasingly becoming a burden to society. As many of the costs for environmental externalities are being imposed, consumers and producers are being forced to internalize and allocate the environmental costs associated with their consumption and production. We cannot expect to meet the future needs of society simply by extending existing infrastructures or conducting business as usual with a reactive stance towards environmental concerns. Finally, extensive literature around the world cites the constant need of renovating existing engineering curricula to better respond to stakeholder needs. We still have learning systems that were developed in the 18th century with little change in content and student learning experiences.

B. Urban Transformation and Sustainable Cities

The concept of "cities of the future" sparks the human imagination. From Orbit City and aerocars in the Jetsons cartoons to fantastical real-world constructions in modern Dubai, our vision for urban architecture and infrastructure has driven amazing innovation. But while our imagination is abundant, the earth's energy and physical resources are not. As a result, we may no longer simply ask, "is it faster, more capable, more powerful?" but rather, we must consider the global environmental challenge and ask, "is it part of the problem…or part of the solution?"

Our very definition of breakthrough innovation for future cities must evolve [2]:

- to apply the experiences of our ancestors, who in the days before mechanized mass transportation, built cities that utilized local resources (the supply side) to meet the demands of their inhabitants;
- to gather lessons from ancient cities to assimilate traditional engineering knowledge;
- to apply fundamentals of social and physical sciences; and
- to examine the role of information technology, using ubiquitous connectivity for the collection of data, data mining, and its analysis for effective and efficient decision making.

Planning of future cities will require the integration of the IT ecosystem into the fabric of a city's infrastructure to enable necessary societal and business activities to take place without unduly taxing the supply side and the environment. Consider, for example, the supply side physical infrastructure made up of roads and vehicles. We cannot expect to meet the needs of the society (the demand) by solely relying on extending the physical infrastructure to cope with population growth. Thus, as populations increase and resources dwindle, how will we design and build fully sustainable cities of the future? We must apply tools and methodologies that enable systemic analysis, design, and management based on integrated management of supply and demand [2]. Section II. B discusses a possible framework to address these challenges.

II. ROLE OF IT IN SUSTAINABLE CITIES

According to Infolific (www.infolific.com) information technology in the broadest sense "refers to both the hardware and software that are used to store, retrieve, and manipulate information." Moreover, we are experiencing a fundamental shift from focus on the "technology" to the "information." The new value chain in human information spans from sensing – physical, personal, and social – to storage, to analysis, to visualization; to the ability to securely access and share information and insights. We believe that information technology can transform future cities along the following two axes:

- **IT Services**: Driving the next generation of IT services will be the millions of citizens who will avail themselves of IT services to address their fundamental needs and improve their quality of life. We have the opportunity to transform the world by deconstructing conventional supply-chains and replacing them with sustainable IT services. This transformation can be delivered by an ecosystem made up of trillions of sensors, billions of handhelds and printers, millions of systems, thousands of data centers and print factories [18], [19], [20].
- **Management of Resources**: With data centers at the hub, and pervasive connectivity, the IT ecosystem can enable integrated supply-demand management of critical resources such as power, water, waste, etc.

Interestingly, the IT-led transformation noted above can only occur if IT itself is sustainable. As an example, as energy drives the total cost of ownership of a data center, there is a need for a new paradigm in design and management of the data center that minimizes energy used across its lifetime – from "cradle to cradle". The need for a "least lifetime energy data center" is further compounded as a result of the projected increase in cost of energy [3] and imposition of regulations that address environmental externalities. An architecture for a sustainable data center that delivers on total cost of ownership goals and has the long-term view of addressing the environmental externalities such as carbon dioxide emissions is needed. Indeed, the authors contend [2] that contrary to the oft held view of sustainability as "paying more to be green", sustainable data centers – built on a framework that focuses on supply and demand management - are the lowest cost data centers.

A. *HP Labs Research on Sustainable Data Centers*

Recent studies indicate data center and associated facility energy use currently account for approximately 1.3% of global energy consumption. In the US alone, this share of consumption increases to approximately 2% [17] The massive-scale, intelligent infrastructure required to power modern business can and should be sustainable. A sustainable data center is one in which end-to-end resource consumption, from material extraction and manufacturing, to operation and end of life, is minimized. Since data centers provide useful services, a sustainable data center must also satisfy the performance requirements - known generally as Service Level Agreements (SLAs) - of the hosted services, while reducing the Total Cost of Ownership (TCO) and emissions.

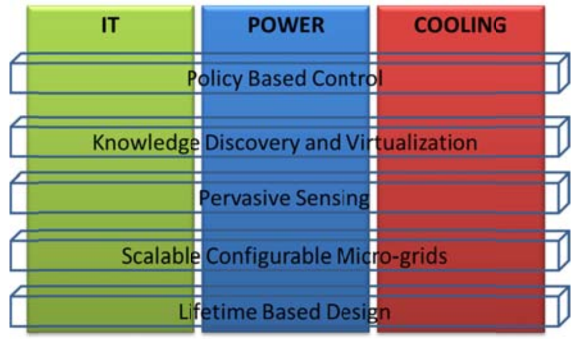

Figure 1. Architecture of Sustainable Data Centers

As shown in **Figure 1**, at HP Labs we have identified five principal areas for integrated design and management to enable a sustainable data center [18]. Each of the five subject areas span the three primary infrastructure components found in data center designs: IT infrastructure (including compute, storage and networking), power delivery infrastructure (including backup power generation and storage, transformers, UPS etc.) and cooling infrastructure which is responsible for removing the heat generated by the IT and Power infrastructures and conditioning the thermal environment for reliable operation. Recently, we've shown how this architecture can be used to design and operate data centers using renewable resources in a manner that consumes no net energy from the public utility grid [19],[20]. Such "net-zero energy" data centers represent the future of sustainable computing. Given the diverse expertise required for designing and operating of each infrastructure element in Fig. 1, multi-disciplinary teams are required for research, design and operation of such facilities. In the sections below, we first elaborate on the content of the curriculum (the five principal subject areas), then on the skills engineering students should possess, to finally propose a learning model.

- **Lifetime Based Design.** Existing data center design approaches are focused on assimilation of discrete components into an operational infrastructure that meets runtime objectives, such as performance and cost targets. From a sustainability perspective, however, the environmental impacts are distributed across the lifecycle of the data center – including the extraction of raw materials, manufacturing of the components and building, transportation, operation, and end-of-life. An integrated approach is needed that incorporates Design for Environment (DfE) principles across the lifecycle, while allowing the data center designer to evaluate the necessary runtime objectives. Such an approach requires expertise in subjects like the environmental sciences as well as software development.
- **Scalable, Configurable Resource Micro-grids,** The data center is built with flexible components within each infrastructure that provide the ability to vary resource use dynamically according to demand. Examples include variable speed fans and pumps in the cooling infrastructure, and virtualization in the IT infrastructure. Necessary subject-matter expertise spans mechanical and electrical engineering to computer science.
- **Pervasive Sensing** continuously monitors the entire data center. There are many measures of interest in a data center - measures that are required to gauge and affect demand-side usage.
- **Knowledge Discovery and Visualization.** Knowledge discovery and visualization (or visual analytics) is a family of mathematical tools for detecting, predicting and visualizing

patterns and anomalies, and can provide better insight to the administrators and agents that manage a data center [4],[5]. Subject matter expertise ranges from data mining and analytics, to domain knowledge.

- **Policy-Based Control.** There are some decisions that must be made too frequently or that are too complex for humans to be effective arbiters. A policy-based control system enables real-time control of data center infrastructure components – IT, power and cooling – based on control theoretic techniques. It utilizes each of the previous layers to control and provision resource use across the data center based on sustainable operating policies (like minimization of energy consumption or emissions). Subject matter expertise includes control theory and domain expertise from mechanical and electrical engineering to computer science.

B. *Beyond the Sustainable Data Center: Sustainable Cities Enabled by Supply and Demand Management*

Just like the sustainable data center, resource management in urban infrastructure relates to holistic management of physical infrastructure at city scale through IT technologies. Unlike industrial age generations, where cities were built predominantly focusing on cost and functionality desired by inhabitants, sustainable cities will require a comprehensive life-cycle view, where systems are designed not just for operation but for optimality across resource extraction, manufacturing and transport, operation, and end-of-life. However, like ancient cities, we suggest a return to traditional engineering knowledge as a foundation of new cities but strengthened with sustainability and IT learning experiences. Indeed, researchers such as S. Ramakrishnan (2001) refer to this as "traditional ecological knowledge" [6] and explore the riches of tribal knowledge in North East India. Examples abound in historical monuments: the Amber Fort in Jaipur, Rajasthan, India, for example, is in an arid region and was built with intricate water harvesting to enable a local micro-grid of water [7].

Our **supply side perspective** calls for using pools of resources of available energy, alongside design and management that minimizes the energy required to extract, manufacture, mitigate waste, transport, operate and reclaim components. This suggests creating numerous "micro-grids" that incorporate various sources of locally-sourced energy, such as solar electricity or wind turbines, that complement centrally-sourced electrical energy. Indeed, seeking available energy in waste streams to augment the distributed energy resources is key to improving efficiency, e.g. using methane from waste water, or methane derived from manure in local farms [8]. These micro-grids need to be scalable and flexible in order to enable a balance in supply and demand.

The **demand side perspective** requires provisioning resources based on the needs of the user by applying sensing, communications, knowledge discovery and policy-based control to the flexible building blocks. Akin to the sustainable data center, the flexible building blocks are micro-grids and other means for generating and distributing resources in the city. An integrated supply-demand system can enable a city to operate and maintain an optimal balance of demand and supply [2].

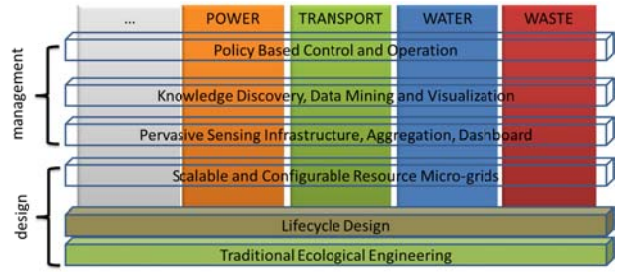

Figure 2. IT-Enabled Architecture for Sustainable Cities

Given this framework, we need a new breed of engineering professionals trained in the engineering fundamentals and the role IT plays in the challenge of building the sustainable cities of the future In addition, these engineers need to have learning experiences on how work in multidisciplinary teams and are capable of optimizing solutions with input from many perspectives, including those not technically related, like social, historic and economic issues.

III. IT and Sustainability Curriculum

A Google search on the keywords "sustainability and IT curriculum" yields over 13,200,000 results[i] covering a wide spectrum of answers covering all levels of education. One can also find extensive dialogue and discussions regarding 'sustainability across the curriculum' aiming at integrating the theme/topic into existing curricula [9]. Yet, among the first few dozen results, none address the curriculum needed to develop the engineering/technical professional in which IT and its role in sustainability are part of the learning experience.

Nevertheless, there is a significant amount of activity in curriculum development and innovation around the world to address sustainability issues. We present a detailed review of existing programs in our prior work [10]. Curriculum development was one of the key topics presented and discussed at the inaugural meeting of the European Platform of Universities Engaged in Energy Research, Education and Training (EPUE), held in TU Delft, in the Netherlands in February 2012. Again, none of the presentations included the topic of IT as fundamental for curriculum innovation. [ii] Yet, of the hundreds of papers presented in this year's ASEE Annual Conference, there was only one (1) session pertaining to integrating sustainability into the curriculum [11].

Our key findings are that while high-quality sustainability curricula already exist today, the majority are focused on environmental or social issues and are housed in departments such as Environmental Engineering or Urban Planning. Few incorporate coursework related to computing or IT for sustainability.

We believe that IT is among the very basic disciplines required to design, build and manage cities of the future. Moreover, to build, manage and make effective decisions, a unique professional

[i] Google search conducted January 19, 2012

[ii] http://www.eua.be/events/past/2012/epue-inaugural-event/presentations.aspx

is needed: one with a blend of knowledge and skills in computer science, mechanical and electrical engineering, economics, social and environmental sciences, and economics, among others.

A. *Innovating the Curriculum*

The curriculum is one of the many variables that help universities achieve their mission and comprises the set of experiences a student has to go through to acquire knowledge and develop skills, in other words, competencies.

We believe innovating or reforming the curriculum is a more efficient approach to respond to ecosystem needs than developing a new curriculum from scratch. In this paper we propose a very well known, effective and efficient process to be used by engineering and computing educators to undertake curriculum innovation: applying the engineering problem solving approach to innovate the curriculum. We provide a more detailed discussion in our prior work [10],[11], including an overview of the *Learning Factory* curriculum innovation model, co-developed by one of the authors of this paper (Morell), and which won the US National Academy of Engineering Gordon Prize of 2006 [13],[14]. This multidisciplinary curricular innovation was successfully conceptualized, developed and implemented in three major US universities in a record time of 2 years. The program was designed and implemented in response to industry needs for an engineer with focused knowledge of product design and manufacturing. It involved course development, learning/laboratory facilities for student hands-on practice based activities, industry collaboration and outcomes assessment. Since its creation, the Learning Factory model (or some of its components) has been adopted by other disciplines in many institutions around the world.

B. *IT and Sustainability Curriculum – The Need*

The first step in curriculum innovation is establishing the need. As we described in section II, IT will become a fundamental tool for the efficient management of scarce resources that have an impact on society, such as water, energy, waste management, or transportation. But as we begin to understand the technical requirements of such a holistic solution for the development of sustainable cities, the need for engineers trained in the disciplines required for each of these competencies becomes apparent. The need for multi-disciplinarity and knowledge of disciplines outside the traditional engineering discipline realm also becomes apparent.

In **Figure 2**, we illustrate how the supply- and demand-side framework of design and management principles developed for Sustainable Datacenters may be applied to sustainable cities as horizontal activities that, in turn, can be used to optimize city "vertical" services such as power (energy) or transportation. Each of these **horizontal and vertical activities** will require engineers that are trained in a set of distinct competencies:

- **Policy-Based Control and Operation**: Control theory from a Mechanical and Electrical Engineering point of view; Industrial Engineering to understand operations and optimization at multi-megawatt scales; understanding of electrical power design; and understanding of mechanical design. This implies a "control systems thread" taught by an Electrical Engineering department or Mechanical Engineering department that combines Computer Science, Mechanical Engineering and Industrial Engineering.
- **Knowledge Discovery, Data Mining, Visualization**: Analytics of this form will become the backbone of many solutions in the sustainability age. The learning will be derived from Mathematics (Advanced Statistics); Computer Science with a focus on data mining and visualization for analytics; and Machine Intelligence. In addition, as many of the devices that will be addressed will be made up of fluid movers, compressors, and so on, knowledge of fluid mechanics and thermodynamics will be important.
- **Pervasive Sensing Infrastructure, Aggregation, Dashboards**: Electrical and Mechanical Engineering principles will be required to understand a variety of methods for sensing and calibration. These will need to be combined with communications to gather data using both wireless and wired networks. Overlapping with Knowledge Discovery, students of this area will specialize in data aggregation leveraging a variety of data mining principles in their "toolkit". Knowledge of the current generation of software methodologies for creating user interfaces will also be necessary to build usable dashboards for network operations centers.
- **Scalable and Configurable Resource Microgrids**: Fundamental principles of Mechanical Engineering and Electrical Engineering, specifically power systems, will drive this area. In addition, strong knowledge of Thermodynamics, Principles of Electricity and Magnetism will be needed to understand energy conversion. Mechanical and Electrical design principles will be needed to understand how to make power grids flexible. Computer Science and Electrical Engineering principles will be needed to understand the means of communication with the physical grids.
- **Life-cycle Design**: This area will require personnel trained in Engineering Economics, Environmental Economics, Materials Science, and Principles of Mechanical Engineering. All these areas will need help from Computer Science learning to build design tools e.g. software and database solutions.
- **Traditional Ecological Engineering**: This foundational area will require understanding of Social Sciences, Environmental Economics and a new area of traditional knowledge gleaned from textbooks of the past. Understanding of Anthropology, Botanical Sciences and Agriculture will be critical. While not specifically addressing traditional engineering, an understanding of the evolution of environmental policy matters over the years will also be crucial for future professionals.

In addition to this list of knowledge, engineering students will also need to continue to develop professional skills that have been identified by accreditation agencies such as ABET [15] and professional societies. These include skills like working in multidisciplinary teams, ability to communicate effectively, awareness of business and environment needs, agility and flexibility, among others. These skills become ever more important for engineers in the sustainability area.

IV. SUSTAINIT: A PROPOSAL TO INNOVATE THE BACHELOR IN SCIENCE IN ENGINEERING (BS) DEGREE

We propose opening a dialogue among the computing and engineering education community focused on the development of a curriculum for the sustainability age at the BS level. We present the first two phases of the process: needs identification and curriculum design. Implementation and outcomes assessment, important components of the process – would need to be considered at a later stage.

A. *The Sustain IT Undergraduate Curriculum*

First, at the undergraduate level, the ***SustainIT*** curriculum relies on engineering fundamentals in the various engineering disciplines. Degree programs naturally inclined to provide fundamental coursework towards this specialization (with their respective required technical courses), include:

- **Computer Science and Engineering**: Software Development; Programming; Operating Systems; Databases; Systems Architecture; Data Storage; Networking;
- **Electrical and Electronics Engineering**: Power Generation; Grids and Micro-grids; Power Transmission; Failure Analysis; Semi-conductor Physics; Chip and System Packaging; Control Theory;
- **Mechanical and Civil Engineering**: Thermal Sciences; Engineering Design; Solid Mechanics; Structures; Manufacturing; Statics and Dynamics; Quality and Reliability;
- **Environmental Science and Sustainability**: Sustainability Basics; Macroeconomics; Microeconomics; Environmental Accounting; Development Theory; Waste Management; Public Policy and Standards; Introduction to Anthropology;
- **Industrial Engineering**: Supply Chains; Operations management; Engineering Economics; Optimization.

Second, students wishing to earn a specialization in ***SustainIT*** would then be required to take a series of guided electives offered across the program, as well as complete other requirements described below. Following the components of the Learning Factory, the ***SustainIT*** curriculum would have the following three features: 1) an IT and Sustainability specialization, track, minor or option[iii] within existing engineering disciplines (consisting of a series of ***Sustain-IT*** electives available to all engineering students to be taken across the program); 2) hands-on learning experiences that would include industry-based projects and could entail an internship in industry or a government facility; and, 3) a multidisciplinary capstone design project focused on an IT for Sustainability theme.

In keeping with the IT-enabled architecture for sustainable cities described in **Figure 2**, the following is our recommendation for a series of guided multidisciplinary electives in the ***SustainIT*** specialization:

1. Fundamental course in IT and Sustainability that would be required for all students wishing to complete the specialization in each of the disciplines.
2. Six directed multidisciplinary electives focused on IT for Sustainability, available to all engineering disciplines:
    a. Policy-based Control and Operation
    b. Knowledge Discovery, Data Mining and Visualization
    c. Pervasive Sensing Infrastructure, Aggregation, Dashboards
    d. Scalable and Configurable Resource Microgrids
    e. Life-cycle design
    f. Traditional Ecological Engineering
3. Other optional electives such as: History of Urban Development, Ecological Engineering, and/or other relevant social science courses in economics, public policy, anthropology, or demographics.

This proposal acknowledges the uniqueness and particularities of each institution. We propose a framework to innovate the engineering and computing curriculum. Each institution or program has the flexibility to develop these (and other courses) that might address the need, and to adapt the ideas presented here to their particular needs and regulations.

For example, engineering disciplines at University X would determine the minimum credits (and number of courses), student experiences, capstone design projects, etc. needed for the minor. The Mechanical Engineering program might suggest the following sequence of courses and experiences to students wishing to earn the ***SustainIT*** specialization:

1. Fundamental ***SustainIT*** course (3 credits)
2. Life-cycle design (3 credits)
3. Traditional Ecological Engineering (2 credits)
4. Scalable and Configurable Resource Microgrids (3 credits)
5. ***SustainIT*** focused Capstone Design Project (3 credits)

Similarly, Computer Science/Engineering might suggest the following sequence:

1. Fundamental ***SustainIT*** course (3 credits)
2. Policy-based Control and Operation (3 credits)
3. Knowledge Discovery, Data Mining and Visualization (3 credits)
4. Pervasive Sensing Infrastructure, Aggregation, Dashboards (3 credits)
5. ***SustainIT*** focused Capstone Design Project (3 credits)
6. Industry internship (2 credits)

Figure 3 illustrates the various components of the S***ustainIT*** curriculum model. As with the Learning Factory model, teaching/learning methods must also be reformed to center on the student's learning and skills development. Hands-on practice-based activities, industry projects, and other activities should be designed and integrated into the learning experience. Finally, and as mentioned earlier, tools and rubrics to assess student learning will also be required to continuously enhance the quality of the program.

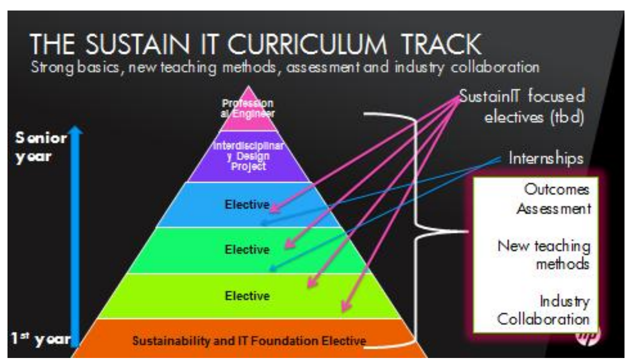

Figure 3: Sustain-IT Curriculum Track

B. *Industry-University-Government Partnerships*

The ***SustainIT*** curricula require students to have hands-on, practice-based experiences, as well as participate in real life industry-based projects. These are a crucial component for developing the kind of engineers that future cities will need.

Industry and governments have a vested interest in collaborating with academic institutions in developing these types of curricular innovations. They will need talent to help design, build and manage future cities. Therefore, collaboration among industry, government, and non-profit organizations is at the heart of the proposed model. They can assist professors in defining the desired profile of the graduating student; provide students with real life projects and provide students and faculty with internship

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[iii] Curriculum innovation alternatives are dependent on each university/program's regulations.

opportunities in real-life engineering settings; and share state-of-the-art technologies being developed in research labs that could influence curricula [16].

V. Conclusions and Recommendations

Higher education is responsible for formally preparing the next generation of business leaders, technical professionals, government officials and educators, and plays a central role in our increasingly technology-based societies and in addressing local, regional and global challenges. The education of computing professionals and engineers must prepare them for the multi-disciplinary nature of the problems they will face.

IT is an important foundation to design, build and manage cities of the future. There is a need to initiate a dialogue around the globe to develop the human resources desired to address future requirements in these areas. As a first step in curriculum innovation, the authors have described the needs for curriculum innovation for the sustainability age and propose a roadmap for innovating the engineering and computing curriculum at the Bachelor's level, called ***SustainIT***. This paper is intended as a baseline and foundation for dialogue among the engineering education community of stakeholders. We encourage not only dialogue around the creation of a novel curriculum model such as the one we describe here, but also a dialogue around a re-emphasis on fundamental engineering principals that includes hands-on learning experiences and experiments that teach problem solving and design, and that provide a solid basis for multi-disciplinary engineers who can integrate traditional engineering with information technology to address the new sustainability challenges facing our society.

The authors recognize that more in-depth research around the world must still be done on 1) integration with existing sustainability and IT curricula and, 2) current and future employers' needs. In addition, curriculum options in sustainability and IT should be developed at the Philosophy Doctorate (PhD) and Masters (MS) degree levels to complement the Bachelor's (BS) degree proposed herein. The latter will be critical to advancing this burgeoning research innovation agenda.

REFERENCES

[1] United Nations Population Division. http://www.un.org/esa/population

[2] Patel, Chandrakant D. "Sustainable Ecosystems: Enabled by Supply and Demand Management". ICDCN'11 Proceedings of the 12th International Conference on Distributed Computing and Networking. Bangalore, 2011.

[3] U.S. Energy Information Administration. Annual Energy Outlook 2011 (Early Release). 16 Dec 2010. p3. http://www.eia.doe.gov/forecasts/aeo/early_prices.cfm

[4] Manish Marwah, Ratnesh Sharma, Wilfredo Lugo, Lola Bautista, "Anomalous Thermal Behavior Detection in Data Centers using Hierarchical PCA," SensorKDD in conjunction with KDD 2010.

[5] Patnaik, Marwah, Sharma, Ramakrishna, "Sustainable Operation and Management of Data Center Chillers using Temporal Data Mining," To appear in ACM KDD, June 27 - July 1, 2009, Paris, France.

[6] Ramakrishnan, P.S. "Structure linked to function: Traditional ecological knowledge and ecosystem complexity." Phytomorphology. 2001. vol. 51, no3-4, pp. 55-74.

[7] Public Health Engineering Department, Meghalaya, India. Rain Water Harvesting Manual. Chapter 2. p 9. http://megphed.gov.in/knowledge/RainwaterHarvest/Chap2.pdf

[8] Sharma, Ratnesh, Tom Christian, Martin Arlitt, Cullen Bash, Chandrakant Patel. "Design of Farm Waste-Driven Supply Side Infrastructure for Data Centers." Proceedings of ASME 2010 4th International Conference on Energy Sustainability (ES2010). May 17-22, 2010. Phoenix, Arizona, USA.

[9] Vanderbilt University. Center for Teaching: Sustainability Across the Curriculum. http://cft.vanderbilt.edu/2010/04/sustainability-across-the-curriculum/

[10] Morell, L.; Trucco, M.; Patel, C. (2011). *SustainIT: Engineering Curriculum Innovation in the Sustainability Age*. WEE 2011: 1st World Engineering Education Flash Week, September 27-October 4, 2011, Lisbon, Portugal.

[11] ASEE 2012 Annual Conference Proceedings, Session M539.

[12] Building Knowledge Economies: Advanced Strategies for Development, World Bank Institute, 2007

[13] Lamancusa, John S., Jens E. Jorgensen and José L. Zayas-Castro. "The Learning Factory—A New Approach to Integrating Design and Manufacturing into the Engineering Curriculum." Journal of Engineering Education. April 1997.

[14] Lamancusa, John S., José L. Zayas, Allen L. Soyster, Lueny Morell, and Jens E. Jorgensen. "The Learning Factory: Industry-Partnered Active Learning." Journal of Engineering Education. January 2008.

[15] ABET. www.abet.org

[16] Morell, Lueny. "5 Things Industry Can Do to Help Educate Better Engineers." Proceedings of the 7th Annual ASEE Global Colloquium on Engineering Education. October 2008.

[17] Koomey, J.G., *Growth in Data Center Electricity Use 2005 to 2010*. 2011, Stanford University.

[18] Watson, B., Shah, A., Marwah, M., Bash, C. Sharma, R., Hoover, C., Christian, T., Patel, C., "Integrated Design and Management of a Sustainable Data Center", Proceedings of InterPACK, San Francisco, CA, 2009.

[19] Bash, C., et. al., "Towards the Design and Operation of Net-Zero Energy Data Centers", Proceedings of ITherm, San Diego, CA, May 2012.

[20] Liu, Z., Chen, Y., Bash, C., Wierman, A., Gmach, D., Wang, Z., Marwah, M., Hyser, C., "Renewable and Cooling Aware Workload Management for Sustainable Data Centers", Proceedings of SIGMETRICS, London, UK, June 2012.