Engineering for One Planet:

Launching a Collaborative Effort to Proliferate Principles of Environmentally Responsible Engineering in Higher Education Institutions

2019

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table of contents

acknowledgements

This paper has been prepared in cooperation with and through the financial support of The Lemelson Foundation, a VentureWell partner since its inception. This work stems directly from the collaborative input, collective thought leadership, and lessons learned from over 150 interviews and conversations with subject matter experts from academia, not-for-profit organizations, government, and industry. We thank everyone who has contributed their valuable time, insights, candor, and support to this initiative.

executive summary

What is the vision for the future of engineering education? What are the student learning outcomes in engineering education that must be integrated into academic programming to cultivate environmentally responsible engineers? How can we work together to create a new future for engineers and our shared planet? What will success look like?

Engineers build our human-made physical and virtual worlds, and many engineers will become the inventors and entrepreneurs that envision and create the future material world we live in. Engineers hold the power to impact and change our planet for good or ill. For nearly 25 years, both The Lemelson Foundation (Lemelson) and VentureWell have been partnering to foster invention and entrepreneurship to improve people's lives. As a pioneering entrepreneurship support organization, VentureWell has supported thousands of early-stage science- and technology-based innovators, many of which have brought sustainable products and services to market. During this time, VentureWell and Lemelson have learned a tremendous amount about the need for environmentally responsible (ER) education in disciplines including engineering, design, and business, and about the gaps and opportunities that exist for higher education faculty members to meet this need.

Despite concerted efforts by both organizations to cultivate environmental responsibility in innovation and entrepreneurship, and the steadfast work many academics and institutions are accomplishing to embed sustainability concepts into their curricula and programs, we aren't collectively doing enough to create and advance environmental responsibility in engineering education in academic institutions across the US. Engineers, especially those who are or will become inventors and entrepreneurs, need help understanding the urgent and large-scale environmental problems we face, the knowledge to consider life-cycle thinking at every stage of product and service development, and the skills and experience to work, communicate, and solve problems across disciplines. It is time to take the next steps to create, implement, and support environmentally responsible engineering (ERE) education, together.

This paper represents the next critical milestone in a series of research efforts and tools development to foster ERE at academic institutions across the US and is a follow-up project from the *Principles of Environmentally Responsible Engineering* roundtable that took place March 27-28, 2019 that was hosted by Lemelson, VentureWell, and The Academy for Systems Change. A top-level recommendation made by the collective group during the roundtable event was to develop an initial strategy document—or white paper—that would clarify what has already been accomplished and to outline the next steps of this collective effort. Ten participants from the roundtable event further contributed to this process through individual interviews to help fill remaining gaps in our collective thinking and to delve deeper into questions that were raised and discussed at the roundtable event.

In this paper, we identify the challenges that we collectively face in developing ERE programs, and outline a rationale and a theory of change for this initiative. The paper provides a timeline of past work, present state, and future opportunities and strives to define the following key elements:

- **"THE WHY"** - an overview and description of the need and importance of the project, as well as the philosophy behind the collaborative approach to developing a framework.

• **"THE WHAT"** - a list of generalized categories of topics for what students need to learn and experience that were defined as a set of four exploratory questions refined at the roundtable:
- What do all engineers need to be able to do?
- What educational outcomes will enable us to make progress?
- What experiences, curricular and extracurricular, do students need to be exposed to, to achieve the desired educational outcomes?
- What systemic changes are needed to make it possible for these curricular and extracurricular experiences to become a reality for all engineering students?

• **"THE HOW"** - examples of critical tools and pedagogical approaches that could be used to achieve the desired learnings and experiences.

We also propose a shared vision, a timeline of critical milestones to serve as a high-level path forward, and make recommendations for next steps to collaborate with stakeholders to develop an ERE "framework." These steps are intended to help create lasting, systemic change in engineering education across US-based academic institutions so that engineers will graduate with the knowledge, skills, and experiences to become leaders and change makers who will design and build with the planet in mind.

Subsequent to this paper, we will continue inviting and working with stakeholders to collaboratively advance this ERE education initiative. As an immediate next step, VentureWell and The Lemelson Foundation will lead an open process to enable stakeholders to develop a set of core principles of environmental responsible engineering that all future engineers should be equipped with. The current language being used to describe this component of the initiative is Environmentally Responsible Engineering framework. The community may guide changes in the terminology as the project progresses.

The framework will define ERE and outline key student outcomes relative to ERE. Recognizing that each higher education institution will approach ERE differently, the framework will outline some common objectives and student outcomes that institutions can agree are important in order to integrate environmental responsibility principles across engineering disciplines. The framework would serve as a collective vision and commitment. The ERE framework phase of the project seeks to define the "What" and next phases will address approaches for disseminating and enabling the integration of the framework in higher education institutions.

This paper will be shared with all participants of the roundtable and the dozens of other stakeholders who have engaged in prior steps toward its development, as well as be made publicly available through Lemelson, VentureWell, and other channels.

background and rationale

Globally, we are facing planetary-scale environmental crises unprecedented in our history. Climate change, air and water pollution, water scarcity, overpopulation, species extinction, deforestation, and soil degradation are just a few of the environmental challenges we face, many of which are exacerbated by the products and services we design, build, distribute, consume, and throw away. We no longer have the luxury of passing the burden of environmental responsibility down the road to the next product iteration, the next entrepreneurial endeavor, or the next generation. We are now at the point in our collective human history that we can no longer ignore the planet in our cost-benefit analyses, economic and business decisions, and product designs. Further, we can no longer take the Earth's limited resources for granted. It is clear, we are now in crisis mode and the time to act is long overdue.

Engineers are one of the largest professional groups that invent new products and services and build our material world. They are tasked with finding technical solutions for our communities, businesses, and governments. It is critical that engineering students learn how to ensure their future inventions and innovations are designed, developed, and distributed in sustainable ways throughout their careers. Engineering education is a key lever for change—yet an understanding of the principles of responsible engineering, and the skills needed to implement them, have not been integrated into educational preparation for the vast majority of engineering students. A clear opportunity exists to forestall future unintended negative impact by preparing future engineers and designers to invent with our planet in mind.

Although Lemelson and VentureWell have taken steps to cultivate environmental responsibility in innovation and entrepreneurship with a focus on engineers, and many academics and institutions are working to embed sustainability concepts into their curricula and programs, we are not collectively doing enough to create and advance environmental responsibility in engineering education in academic institutions across the US. Engineers, especially those who are or will become inventors and entrepreneurs, need help understanding the urgent and large-scale environmental problems we face, the knowledge to integrate life-cycle thinking at every stage of product and service development, and the skills and experience to work, communicate, and solve problems across disciplines. It is time to take the next steps to create, implement, and support ERE education, together.

This white paper represents the next critical milestone in a series of research efforts and tools development to foster ERE at academic institutions across the US. It is a product of the collaborative input, collective thought leadership, and lessons learned from over 150 interviews and conversations with subject matter experts—inventors, students, alumni, faculty, and administrators—from academia, not-for-profits, government, and industry. Over the course of the past two years we have interviewed individuals at undergraduate and graduate level academic institutions and community colleges, from both public and private sectors, that represent the disciplines of engineering, design, and business. This paper summarizes the efforts and findings from numerous previous ER-focused research projects, tools development, and professional convenings.

This white paper follows on years of work including research, grants, and previous meetings. However, writing a white paper was a key recommendation generated at a recent convening, the *Principles of Environmentally Responsible Engineering* roundtable that took place March 27-28, 2019 hosted by Lemelson, VentureWell, and The Academy for Systems Change. At the roundtable, 20 participants representing faculty, nonprofit, business, and government professionals with expertise in sustainable engineering and related concepts came together to start the process of creating a shared roadmap for developing a framework for ERE.

Together, we generated a high-level list of questions that needed to be answered, stakeholders that needed to be engaged, and a number of recommendations to advance this ERE education initiative.

A top-level recommendation of the collective group was to develop an initial strategy document—or white paper—that would serve to clarify what has already been accomplished and outline the next steps of this collective effort. Ten participants from the roundtable were interviewed after the event to further contribute to this process to help fill remaining gaps in our collective thinking and to delve deeper into questions that were raised and discussed at the roundtable event to help us craft a white paper.

In this paper, we identify the challenges that we collectively face in developing ERE programs and outline a rationale and a theory of change for this initiative. The paper provides a timeline of past work, present state, and future opportunities and strives to define the following key elements:

- **"THE WHY"** - an overview and description of the need and importance of the project, as well as the philosophy behind the collaborative approach to developing a framework.
- **"THE WHAT"** - a list (i.e. ERE Framework) of generalized categories of topics for what students need to learn and experience that were defined as a set of four exploratory questions refined at the roundtable:
    - What do all engineers need to be able to do?
    - What educational outcomes will enable us to make progress?
    - What experiences, curricular and extracurricular, do students need to be exposed to, to achieve the desired educational outcomes?
    - What systemic changes are needed to make it possible for these curricular and extracurricular experiences to become a reality for all engineering students?
- **"THE HOW"** - examples of critical tools and pedagogical approaches that could be used to achieve the desired learnings and experiences. Further research will also be done to identify approaches to enable adoption of the ERE framework in higher education institutions.

Lastly, we outline a recommended list of focus areas as the next steps to advance this effort beyond this paper in order to create an ERE framework, which includes a high-level path of critical milestones and a shared vision for the future of this initiative. These efforts, and those to follow, are intentionally building an inclusive and committed community of practitioners and advocates who are coming together to envision, formalize, and support the development of ERE education with the ambitious goal to create a new future for engineers and our shared planet.

the why

> **"An environmentally responsible invention can come from any sector. It's not just a term used to describe breakthroughs in renewable energy or technologies for purifying unsafe water. Rather, it is a way to describe any invention that has the smallest environmental footprint possible—from the way a product is conceived and prototyped, to the materials sourced in its production, to the end of its life-cycle and how its component parts ultimately break down. We must reduce the negative environmental impacts at each step in the process."**
>
> *(The Lemelson Foundation, 2017)*

Imagine a world where every engineering graduate—no matter the subdiscipline—were equipped with the tools and experiences to assess and measure environmental impact, in which it would be impossible for an engineer to graduate without a basic understanding of the critical environmental issues of our time and where engineers would have the critical thinking and leadership skills to face these issues as confident change agents. We believe it would have a transformative, cross-cutting effect by cultivating the very people and systems that can make the greatest difference for positive environmental impact for today and into the future.

While inventions have helped solve some of our greatest environmental challenges, too often the tenets of environmental responsibility are absent from the invention process itself. Often in the worlds of invention, entrepreneurship, and business, the conversation turns to trade-offs between profitability and sustainability in the process of product development. Most often, the decision is made to focus on short-term profits and do not take into account the full range of long-term environmental impacts. We, among many other sustainability-focused stakeholders, are seeking ways to affect long-lasting, systemic change. Stakeholders from across sectors are driving the demand for environmental responsibility, from climate conscious students and education leaders who are passionate about preparing our engineers and inventors for a resource-constrained future, to business leaders who incorporate sustainability into the world's most competitive companies, to countries that are leading the charge to implement the United Nations 2030 Sustainable Development Goals (SDGs).

the business case for why now

The private sector—for example, the consumer goods industry—has become increasingly aware that sustainable innovation is not only the right thing for life on Earth, it can itself be a winning business model. Industry has a growing interest and is seeking engineers who have already been trained with an environmentally responsible mindset in order to advance their sustainability initiatives, reduce their negative environmental impacts (which can have significant costs and penalties attached to them), and satisfy the demands for more environmentally-friendly products from their valued and eco-conscious customers.

Many positive, planet-first changes have been made to corporate initiatives and governmental policies, often due to local, regional, national, and international demands and crises. Despite the US government's recent decisions to make major rollbacks to environmental rules and policies,[1] the global political appetite for ensuring business is a part of the solution has shown a clear positive trajectory in recent years. Today, over 180 parties have ratified the Paris Agreement that entered into force in November 2016, where each party would make concerted efforts to mitigate greenhouse gas emissions.[2] Leading the charge to invest in renewables is China, at $84 billion in 2014, followed by the European Union at $58 billion.[3] The green economy is beginning to have noticeable impact on global, as well as US, economies and employment rates, although there is still a lot of room to grow in this arena.

A snapshot below shows recent and positive changes to the green economy that will continue to influence the market demand for ER-focused engineers. Although some examples pertain more broadly to the need for sustainable solutions to environmental problems rather than demonstrating ERE approaches, these examples demonstrate clear trend lines toward the rapidly growing need for engineers with knowledge of and experience with ER best practices:

- Over 3.2 million Americans work in the clean energy sector, three times more than currently work in the fossil fuel industry.[4]
- The top two fastest growing occupations from 2016 to 2026 are predicted to fall into the fields of solar and wind technologies, with a projection of 105% and 96% change in employment in the US, respectively,

compared with the average growth rate for all occupations at 7%.[5] Further, nearly 140,000 new engineering jobs are expected over the 2016–26 decade.[6]

- In 2013, there were 3.4 million Green Goods and Services jobs, accounting for 2.6 percent of total US employment;[7]
- Nearly 70% of participants in a 2019 consumer study ranked sustainability as "important," regardless of gender or age, and 35% stated they would pay 25% more than the original price for sustainable products.[8]
- 85% of S&P companies (Standards and Poor's 500 Index) published sustainability reports in 2017, demonstrating a major increase since 2013 when less than 20% of companies shared sustainability reports. This change reflects an increasing demand for material, relevant, comparable, accurate, and actionable ESG (environmental, social and governance) disclosure from companies from all categories of investors.[9] Currently, nearly 60 total stock exchanges worldwide have environmental listing requirements, up by 28 since 2017;[10]
- Nearly 600 companies have committed to science-based greenhouse gas (GHG) emissions targets,[11] and companies' GHG emissions fell by 9% compared with 2013 levels;[12]
- Almost 30 more companies have set carbon and water targets since 2015. However, current carbon targets contribute just 16% of the reductions needed by the top 1,200 global companies to align with the Paris Agreement two degrees Celsius goal.[13]
- Nearly 60% percent of respondents in a recent study of nearly 2,500 companies said their organizations were more engaged with sustainability than they were two years ago.[14]
- Over 2,000 businesses and investors have signed the *We Are Still In* declaration, launched in 2017, to pledge their continued allegiance to the goals of the Paris Agreement.[15] Major companies like Unilever, IBM, IKEA, L'Oreal, and REI, are part of the movement, indicating their unflagging support for green jobs;[16] and
- More than 350 organizations, including large, global consumer businesses such as Danone, H&M Group, L'Oreal, The Coca-Cola Company, and Unilever, have signed the New Plastics Economy Global Commitment to eliminate plastic waste at its source. This represents a reduction in 20% of global plastic packaging.[17]

why engineers?

To make long-lasting systemic change, engineers and engineering programs offer critical opportunities for intervention because engineers create, construct, and massively proliferate the technologies and products of tomorrow. Engineers are the linchpin to ensure that the things we build are ultimately compatible (or not) with the health of the planet and the lives it sustains. Engineers build our human-made physical and virtual worlds, and many engineers will become the inventors and entrepreneurs that envision and create the future material world we live in. Engineers hold the power to impact and change our planet for good or ill.

While inventions take many forms and are created by all different types of people, there is a pressing need to address the impact of engineers and their physical inventions. Almost all engineering-based inventions need to be made or manufactured to some degree, and it is inevitable that somewhere along the line most inventions involve engineers. Additionally, the importance of understanding the impacts on the environment of products throughout their life-cycle are not well understood and appreciated in the engineering community. To ensure a better future for all people and the planet, it is critical to cultivate change in the practice of engineering and education of engineers, and to do so quickly. Focusing on engineers and engineering education is a critical starting point but we recognize that a shift in ER thought and practice needs to extend to all disciplines and society as a whole.

While there have been numerous positive developments in the field of engineering and industry, the exposure that engineering students and professional engineers have to principles of environmental responsibility is not ubiquitous. Given how critical engineers are to the creation of physical products and inventions, we are committed to working with partners and stakeholders to put in place the systems that expose *all* engineers to the principles they need to keep in mind in order to minimize products' impact on the environment.

The potential for impact is enormous if we start with engineers at their earliest stages of professional preparation, rather than attempting to retrain professional engineers down the road. Below is a snapshot of the current statistics about engineering education today:

- Currently over 600,000 students are enrolled in undergraduate engineering programs in the US. This is a 54% increase since 2008,[18] and
- More than 4,000 engineering programs have been accredited by the Accreditation Board for Engineering and Technology (ABET) at nearly 800 institutions in over 30 countries around the world.[19]

From an accreditation standpoint, taking environmental considerations into account has been in ABET's *Criteria for Accrediting Engineering Programs*—the accepted attainment standards that will prepare graduates to enter the professional practice of engineering—for over a decade. Two of ABET's seven student learning outcomes specifically call out sustainability and the environment, as follows:

- "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability," and
- "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context."[20]

These redundancies and modifications might offer new opportunities for positive change with regard to embedding environmental responsibility in engineering curricula, since higher education institutions will be actively seeking new ways to meet ABET's refined student outcomes.

Subdisciplines offering deep exposure to sustainability and environmental responsibility principles have been developed already—chemical engineering and green chemistry are pioneering in this regard.[21] Despite these curricular advancements and the ABET learning outcomes requiring consideration of social and environmental impact, engineering students are not ubiquitously exposed to core principles of environmental responsibility. In addition, there is a disconnect between what many students do and want in their personal lives, and how they build products and businesses. In 2016, VentureWell conducted an assessment to understand the impact of their newly developed guide to sustainable design called *Inventing Green: A Toolkit for Sustainable Design*[22] which they had tested during E-Team student venture training workshops. Fascinatingly, they discovered that although 70% of students stated that personal sustainability was of "utmost" importance, 60% had not considered the potential environmental impacts of their designs before using the Toolkit.

In-depth exposure to environmental responsibility for students in all engineering sub-disciplines therefore remains a critical challenge. It is especially challenging at the undergraduate level, where a large number of students are first introduced to the professional disciplines, form their identity as inventors and innovators, and have the opportunity to develop and test their ideas in the lab or field for the first time. Fostering literacy in the principles of environmental responsibility among all engineering students is imperative to address urgent societal needs and to understand the potential environmental benefits and unintended negative consequences associated with their inventions and innovations. A greater understanding of these fundamental principles must be underpinned with preparation of emerging engineers with the vocabulary, tools, critical thinking experience, and leadership skills to drive transformative developments in the 21st century and beyond.

why a collaborative approach?

We believe listening to and working side-by-side with stakeholders and constituents to develop a shared vision and ERE framework for change that we all believe in, invest in, and will endorse, is the only way to make effective, systemic change to engineering education. As we have briefly mentioned and will provide more detail about later in the paper, each of the ER-focused efforts thus far represent collaborative efforts, including the development of this white paper. The publication of this white paper is the beginning of work together as an expanding collaborative community of stakeholders to advance this ERE education initiative. An important next step is the creation of an ERE framework—a list of universal principles for environmental responsibility that all engineers should be exposed to and educational outcomes that all engineers need to achieve. The community-driven ERE framework development process is a necessary next step but not the end point of this initiative. Next steps will include developing and deploying approaches to increase adoption of the ERE framework in higher education institutions.

Solving complex challenges requires working outside of siloes, crossing disciplines, and working across aisles. By aligning on our common values, discovering points of consensus, and leveraging shared motivations, we will collaboratively arrive at impactful decisions, guiding principles for change, and ensure a collective investment in shared, meaningful outcomes. Leading champions of environmentally responsible engineering education from academia, business, government and NGOs identified stakeholder groups critical to engage, including: faculty, students, university systems and administrators, professional associations, industry, funders, media, government, NGOs, and the Earth and other unheard voices (e.g. flora/fauna, climate refugees).

By implementing a collaborative process that involves key stakeholders to develop our collective voice, we are consciously building an inclusive and committed community of practitioners and advocates who will come together to envision, formalize, and support the development of an ERE education initiative with the ambitious goal to create a new future for engineers and our shared planet.

developing a theory of change

To clearly define the problem, we are seeking to address and create a common understanding of the approach we are taking, we offer a theory of change (ToC) that outlines a basic systemic change strategy to move forward in ERE education in US-based institutions of higher education (see Figures 1 and 2). The purpose of the ToC is to enable a collective dialog to define how our strategies and actions will achieve change, communicate a vision for change, and identify expected results for change.[23,24] The ToC below (Figure 1) is intended to serve as a tool to guide and inform current and future collective efforts.

We propose a collaborative approach, where Lemelson, VentureWell and a community of engaged and committed stakeholders work together to integrate principles of environmental responsibility to effect systems level change to engineering education that will directly impact the knowledge, skills, and experiences of engineering students, and ultimately, have positive impacts on environment, society, and the economy. Graduates of programs incorporating ERE education will create positive impacts on our world through their professional careers. Ultimately, we envision that graduates from all disciplines would have an ER focus and it will simply be a natural way of seeing the world.

Specifically, there are three target populations for cultivating change that will directly impact the opportunities provided to all engineering students—our service population—who will receive an ERE education: individual-level (students, faculty, administrators), institutional-level (curricula, programs, departments, degrees, accrediting bodies), and professional-level (professional engineering societies, industry). By working together, utilizing both top-down (i.e, institutions, administrators) and bottom-up approaches (i.e., faculty, students), we can achieve our shared core outcomes to: produce more ERE graduates, cultivate a new cultural norm where ERE is ubiquitous and universally accepted in engineering programs, and, ultimately, there is an increase in ER-focused science and technology inventions and entrepreneurship.

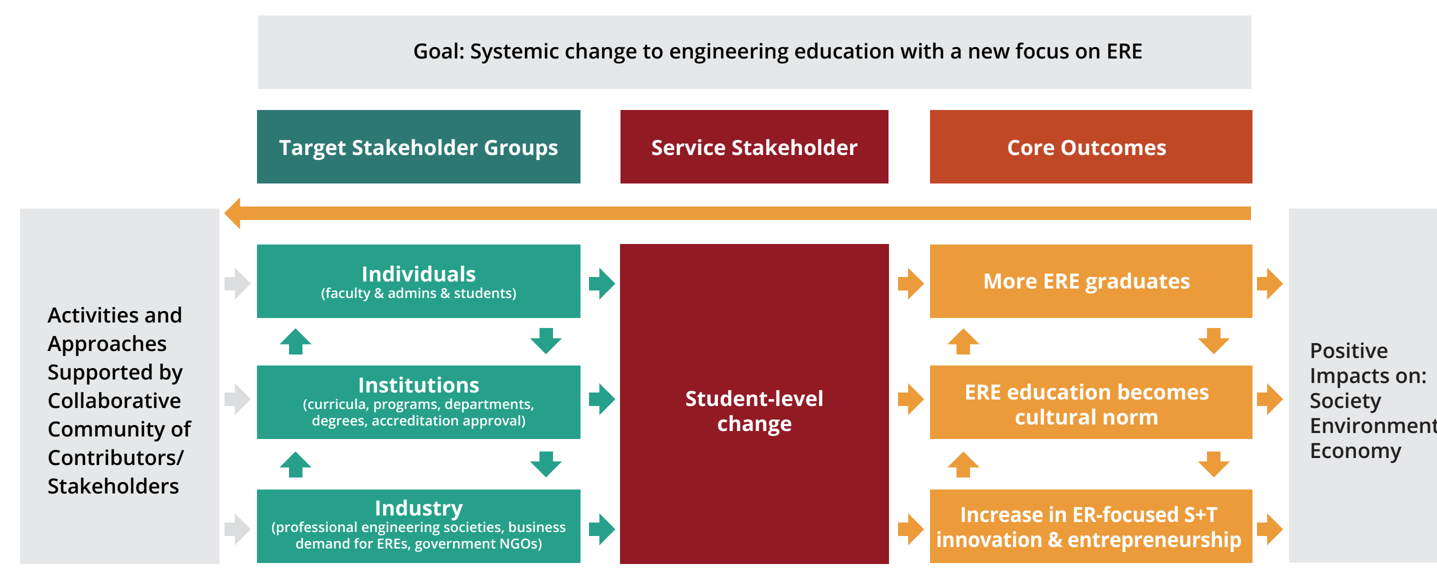

Figure 1. Systemic-level Theory of Change for Environmentally Responsible Engineering in Higher Education for US-based Institutions with Delineated Target and Service Populations and Core Outcomes.

summary of our environmental responsibility-focused efforts to date

Below we share a summary of the combined efforts of Lemelson and VentureWell to advance ER-focused initiatives over the past several years. We believe it is important to share a synthesis of the many collaborative efforts have already been accomplished by these two organizations in order to have a common starting place for the next phase of the ERE education initiative—the collaborative development of the ERE framework—and as a means to engage and bring new stakeholders up to speed on what we've been doing together and where we are headed in the future as a collective group of committed community members.

inventing green initiatives

Lemelson and VentureWell have taken concrete initial steps to support faculty in their efforts to embed environmental responsibility principles within science, technology, engineering, and science (STEM) education through innovative curricular and co-curricular approaches. See appendix A for a complete list of ER-focused efforts conducted by Lemelson and VentureWell.

Lemelson has been advancing this effort in innovation and entrepreneurship efforts since integrating environmental responsibility in its programmatic strategy in 2012. Lemelson integrated environmental responsibility into its grant guidelines, requiring all grantees to demonstrate commitment to environmentally responsible invention. It also issued requests for proposals (RFPs) to grantees for the development of courses, tools, and resources to support its *Inventing Green* initiative. Recently, Lemelson supported the development of several new free critical "Inventing Green" tools targeting early stage innovators, faculty, and startup accelerators to guide the integration of ER and social responsibility; they have included:

- VentureWell's *Inventing Green: A Toolkit for Sustainable Design*,[25] that helps early-stage inventors understand how the life-cycle of their products will affect the environment. The toolkit includes a video series—that highlights several sustainability initiatives that VentureWell has supported through faculty grants over the past decade—and several resources that can be used together, a la carte, or within short workshops, multi-day accelerators, or as part of a university-level engineering or design course. This tool has been downloaded nearly 350 times since it was launched in spring 2018.
- NESsT's *I2E Inventing Green Tool*,[26] that was designed for companies to simplify the process of assessing and tracking environmental impact, and
- Presidio Graduate School's *Business Sustainability Booster (BSB)*[27]—an overlay for the well-known *Business Model Canvas*[28]— that guides entrepreneurs through a set of questions to make their business models more socially, environmentally, and economically sustainable.
- VentureWell's *Tools for Design and Sustainability (TFDS)*,[29] a collection of content, exercises, and examples for designers, inventors, and startup founders who are curious about sustainable options and are seeking practical advice for taking action toward integrating sustainability principles into their work. The TFDS webpage has had 250 unique visitors since its public launch in fall 2018.

Similarly, VentureWell has been making concerted efforts to advance ER in its offerings. In 2018, VentureWell launched an annual *Sustainable Design Faculty Grant* where awards of up to $30,000 are offered to support faculty and staff who were committed to integrating ER practices and methodology into their innovation and entrepreneurship curriculum and to foster the opportunity to create or transform courses that promote sustainability in STEM entrepreneurship. To further the impact of this funding opportunity, VentureWell launched an annual interactive workshop to equip ER educators with the knowledge and skills to integrate sustainable invention and innovation curriculum and practices into their curricula. The workshop enables participants to learn from experts as well as from one another, to build their ability to apply and teach sustainable design tools, and to refine their plans for project implementation. During the first year, VentureWell awarded 12 grants to 11 universities.

Working with VentureWell and other partners, Lemelson has also coordinated several workshops and research activities to identify gaps and opportunities for enabling future inventors to be environmentally responsible in their efforts with a focus on engineering education. We describe lessons learned from several key efforts below.

advancing ERE in education

As part of the effort to understand and advance ER best practices in engineering, a research project was conducted in 2017 to examine and analyze a comprehensive collection of best practices for current ER invention-, innovation- and entrepreneurship-focused programs being implemented around the globe in higher education.[30] Twenty-five in-depth interviews were conducted with academics and subject matter experts in academia, and alumni and inventors in industry.

High-priority recommendations derived from the results of the study were used to inform Lemelson's next steps in supporting ER educational efforts.

This study unearthed best practices and barriers for teaching inventing green in higher education and developed strategic action for increasing the capacity and scale of leading educational approaches. Top-tier recommendations included: 1) invest in faculty by supporting faculty development and education to overcome the barriers of status quo faculty and lack of faculty understanding, 2) foster "soft skills" development in students by cultivating "life" skills in students to ensure that they will be able to apply sustainability frameworks and challenges in all capacities, and 3) develop key external partnerships through the cultivation of real-world experiences for students in communities, companies, NGOs, and government to groom them to become valued employees.

Another outcome of this work was the discovery of a study that had been funded by the Environmental Protection Agency (EPA) in 2008 that had a similar vein of research and similar findings.[31] After reviewing the EPA study, we were left with several unanswered questions and a follow-on study to the EPA report was conducted to answer these questions (i.e., how did the EPA research come about? what progress has been made (or not made) as a result?).[32]

Through a series of informal interview questions with three of the EPA report authors, we sought to better understand how the EPA research came about, what they learned, what progress has been made (or not made) as a result of what was learned, and why. We learned, since the EPA study, several authors had received additional National Science Foundation (NSF) grants to: support train-the-trainer workshop efforts and the development of an engineering resource website called the Center for Sustainable Engineering, support a short follow-up survey conducted in 2010, and host a sustainable engineering curricular content workshop in 2014. Interviewees pinpointed the lack of: funding, change in accreditation standards, incentives and accolades, and easy-to-find, quality resources as the key barriers for adoption and integration of ER education in the field of engineering.

The study revealed that there was no "silver bullet" curricular strategy. Instead, respondents valued teaching a variety of topics to integrate ER including systems thinking, environmental impact measurements and metrics, business and economic considerations, and social responsibility and social impacts.

The follow on study determined the biggest challenge with integration of environmental responsibility principles into engineering curriculum today is that it is a systemic problem that involves all levels of academia; therefore it requires a systemic solution. The study suggested that a multipronged approach be used that would support and invest in faculty by overcoming academic barriers and works in partnership with professional societies to positively influence ABET. Four key recommendations were rendered to create systemic change: 1) support faculty development and resources, 2) develop faculty incentives, 3) rally academic allies, and 4) lobby powerful organizations.

As a means to move toward the first recommendation, Lemelson and VentureWell convened an interactive workshop in March 2018 with interviewed faculty and other experts to reflect on the study findings and their own experiences, revealing common themes regarding barriers and opportunities to increase the capacity to intertwine environmental responsibility with invention and innovation education. Prioritized opportunities were to develop faculty through curriculum sharing and faculty training, align incentives among partners within institutions, and include institutional leadership. Barriers noted were the lack of cohesion through the use of different terminology across disciplines and institutions, students' limited prior experience with systems thinking, and misconceptions about the scientific rigor of pursuing sustainability. New ideas put forward were tapping into student enthusiasm for having a positive impact and going beyond teaching technical skills to incorporating a values-driven curriculum.

roundtable

Most recently, in March 2019, an interactive roundtable event brought together 20 leaders from higher education, nonprofit, industry, and government with expertise in sustainable engineering, green chemistry, and other related areas. Prior to the roundtable, participants were interviewed about key ideas, tools, and resources. *Snapshot of Recommended Resources from Pre-Meeting Interviews from Roundtable Event Participants*[33] and *Highlights of Findings from Pre-Workshop Participant Conversations for Roundtable Event*[34] documents were created and shared with roundtable participants as part of the pre-event preparations. Key learnings from this effort included the direction to integrate principles of environmental responsibility into core engineering education, rather than as standalone electives, core courses, or programs. Participants identified five key barriers keeping students from receiving this type of education:

- not seen as a priority by institutions,
- lack of faculty training or prioritization,
- disciplines that operate in silos (especially in the U.S.) and face institutional barriers to collaborating across disciplines,
- applied, real world opportunities for learning are not readily available to students, and
- not seen as valuable in professional practice.

Other key outcomes included a "healthy impatience for creating change," and the recognition that the systemic changes needed in engineering education can only come by working collaboratively and generating buy-in from a broader group of stakeholders and supporters.[35]

At the two-day roundtable, participants engaged passionately while sharing their personal experiences and challenges, reflecting on the urgent need to identify scalable levers for impact, and grappling with the inherent value of creating a "framework" for ERE. Together, roundtable participants generated a high-level list of questions that need to be answered and stakeholders that need to be engaged to develop and drive forward an ERE framework. As noted, based on the needs reviewed in this paper, this framework is not intended to generate a new engineering discipline, but instead it would be a framework that can be used to cross-cut all engineering disciplines and subdisciplines that will integrate the highest priority concepts, values, skills, and experiences all engineering students need to learn in order to engineer with the health and sustainability of the planet in mind.

By the end of the roundtable, participants achieved initial alignment around a number of key elements needed to advance this initiative. The focus areas below were recommended as a starting point and will benefit from having clearly identified project leader(s) as well as strategic contributions from roundtable participants and other critical stakeholders:

- Develop an initial strategy document that clarifies the "why/why now" (i.e. philosophy and urgent need for this work), the "what" (initial list of topics of student knowledge/experiences and existing tools and resources), and the "how" (vision and high-level roadmap with clarity on stakeholder engagement opportunities).
- Consider developing a system map of engineering education in order to more fully understand the current landscape.
- Through coordinated, multi-stakeholder input, set and refine parameters for a framework that clarifies what ER engineering is, and the core questions, goals, and values that define it.
- Develop communication tools, including a project overview, email messages, and scripts to use with key stakeholders in order to solicit their review and feedback, and ultimately to recruit signatories on an updated framework.
- Collect and compare existing frameworks and other relevant resources to create an initial repository that can be shared with stakeholders.

the what

We examined "the what" questions of this initiative by developing a set of four exploratory questions refined with input from prior stakeholder conversations and from roundtable participants:

- **What do all engineers need to be able to do?**
- **What educational outcomes will enable us to make progress?**
- **What experiences, curricular and extra-curricular, do students need to be exposed to in order to achieve the desired educational outcomes?**
- **What systemic changes are needed to make it possible for these curricular and extra-curricular experiences to become a reality for all engineering students?**

The first three questions are guiding the collaborative development of a comprehensive list of topics of student knowledge, skills, and experiences that will be used to articulate desired educational outcomes for the ERE framework and to compile a list of existing critical tools, guides, and pedagogical and delivery approaches to bring ERE activities into engineering courses. The fourth question is helping to identify and prioritize ways to cultivate systemic change in engineering education for future ERE courses, curricula, programs, degrees, and institutions.

student knowledge, skills, and experiences

As a synthesis of all of the prior ER-focused efforts (e.g., workshops, research projects, roundtable), we developed a comprehensive list of topics that would prepare students to become engineers who are knowledgeable of and utilize ER best practices in their work. The topics fell into two broad categories: 1) knowledge and content, and 2) skills and experiences. (See appendix B for the detailed list of suggested student learning outcomes clarified through follow up interviews.) In the coming months, we will coordinate a variety of opportunities for stakeholders to comment and suggest refinement and prioritization of these categories, enabling a broad community of invested stakeholders to co-create an ERE framework to be disseminated next year.

knowledge and content

Knowledge and content were broadly defined by the questions, "why should students learn this? what do they need to know about?" and broken down into four topical areas: systems thinking, environmental and sustainability literacy, business and economic considerations, and social implications.

Systems thinking comprises the understanding and awareness of the system outside of their products and/or services, as well as an understanding of systems thinking practices including approaches and perspectives, that will go beyond behavioral stock and flow, and system archetypes.

Environmental and sustainability literacy included: knowledge of life cycle thinking; understanding of key environmental laws, ethics, policies, and agencies; a knowledge of basic facts/data about important (current/past/future) environmental issues and the motivations for working to solve environmental challenges (i.e., climate change; pollution, toxicity, and public health, water scarcity, loss of biodiversity, etc.); knowledge of the abiotic and biotic natural capital; and knowledge of key ecosystem services and functions (e.g., provisioning, regulating and maintenance, cultural and supporting services, including cycles (i.e., material cycles, energy cycles). For example, are engineers aware of and thinking of ways to maintain and regenerate the ecosystem services they will employ in their designs, such as the water cycle or energy cycle, or are they aware of the environmental laws and policies that impact their ability to implement their designs or constrain their work?

Business and economic considerations consisted of gaining the knowledge of costs and value to the environment and society beyond, and an understanding of different ER-focused business, revenue, and entrepreneurship models. For example, are engineers aware of designations such as Certified B Corporations, how sustainability reporting and ESG disclosures influences S&P Index businesses, and the difference between long- and short-term business goals and valuations?

Social implications focused on an understanding of how designs cause social impact and the role of social responsibility. Also it was recognized that an understanding of social justice, laws, and policies, ethical literacy, and knowledge of the United Nations Sustainable Development Goals (SDGs) are needed. For example, do engineers consider the impact to the people who will build their designs and to those that will be influenced by products' disposal or disassembly?

skills and experiences

Skills and experiences were broadly defined by the questions, "what technical and practical skills must all engineers have to be competent in principles of environmental responsibility? what do they need to experience and practice to lead change?" The identified skills were broken down into the two subcategories of technical skills and leadership skills.

Technical skills were further split into two areas: environmental impact measurement (including discipline-specific technical skills) and materials choice. Environmental impact measurement skills and experiences entailed the ability to conduct life cycle assessments and analyses as well as to assess broader energy implications and EHS standards (environmental, health, and safety; i.e., chemical hazard assessments, how to research chemical safety, etc.).

Materials choice skills encompassed the abilities to: assess and select green materials (e.g., choice, flows, and circularity), assess EHS aspects of materials (e.g., toxicity, green chemistry, etc.), and design for the environment based on discipline-specific technical skills (e.g., light-weighting, materials resourcefulness and savings, leverage recyclability and upcycle-ability, and energy efficiency).

Leadership skills comprised critical thinking and communication skills. Critical thinking skills consisted of the abilities to: define problems well in order to work on things that matter, approach and solve problems with creativity, conduct research and user experience studies, make ethical and empathetic decisions, innovate with an understanding of the difference between radical and incremental innovation, experience different perspectives, and become a global citizen that embraces the contextual relevance and importance of local, regional, national and global perspectives.

Communication skills covered the ability to communicate through all mediums (written, graphic/visual, oral, interpersonal communication skills) in order to be able to sell ideas, advocate for change and the underrepresented, drive organizational change, maximize team effectiveness, and work well with others and across disciplines. The ability to lead, interact with, and collaborate on cross-disciplinary teams as well as to manage schedules, time, and people were identified as key communication skills for engineers.

Interviewees commented that the amassed list of concepts, skills, and experiences was, *"excellent but way too much."* In order to tackle this idea of how to pare our long list of topics, we asked interviewees which of the items on the list were their top three choices. Put another way, we asked them if they could only select three concepts, skills, or experiences to integrate into existing engineering classes, which would they be. The following topics were selected the most often as a top three choice by interviewees (numbers in parentheses indicate the frequency the topic was chosen; note that not everyone interviewed picked three choices): environmental and sustainability literacy (6) including life cycle thinking, systems thinking (4), and environmental impact measurement (4).
These selections show some overlap with our earlier research conducted in 2018,[36] where over 60% of respondents positively mentioned the following core topics during interviews: business and economic considerations, social responsibility and social impacts, and systems thinking. Understanding the most critical topics to teach will be examined with a broader group of stakeholders through the framework development process to get a clearer picture of what is considered the most crucial to the collective group and to develop a pared list of required student learning outcomes.

fostering systemic change

As part of our "what" series of questions, we asked participants to answer the question, "what systemic changes are needed to make it possible for these curricular and extracurricular experiences to become a reality for all engineering students?" Three main themes emerged from the interviews of key systemic changes that need to happen to ensure that the ERE framework is supported and impactful:

1) accrediting bodies need to recognize that sustainability should be a main focus in engineering curriculum,
2) academic programs need to require teaching sustainable methods, and
3) funding needs to be set aside to support sustainability efforts. This is a question that we need to continue to ask in the next stages of this work to get more clarity on the best approaches to effect systemic change in engineering education.

the how

We have summarized the critical tools and guides, and pedagogical approaches and delivery methods that could be used to achieve the desired learnings and experiences listed above. These suggested resources were gleaned from our learnings during prior ER-focused efforts (e.g., workshops, research projects, roundtable), and were expanded, clarified, and specified through follow up one-on-one interviews. These resources are shared in an emergent state and we intend to continue to bolster, refine, and prioritize resources by engaging with a broader group of stakeholders as the ERE framework is developed in the coming months.

critical tools and guides

Numerous critical tools and guides were identified through research and stakeholder conversations. We organized the critical tools and content guides using the broad categories listed above. We acknowledge that this list of tools represents only the initial stages of this effort; we will continue to invite stakeholder participation and engagement in the next stages of this initiative. (See Appendix C for the detailed list of the critical tools and guides previously suggested.)

Numerous systems thinking tools were suggested that ranged from the work of Donella Meadows to biomimicry to circular design strategies to the TFDS hosted on VentureWell's website. Environmental and sustainability literacy tools included the Sulitest, Story of Stuff resources, and the Water-Energy Nexus guide developed by the Department of Energy. Tools to support business and economic considerations included the Business Sustainability Booster and the T-Plan, Cambridge University's model for facilitating the process of getting technologies to market. Tools to support the development of social implication skills and experiences were thin and need bolstering yet included the SDGs, the Ten Principles of Justice, Sustainability and Peace created by Vandana Shiva's Earth Democracy movement, as well as IDEO's Human-Centered Design Kit.

A plethora of critical technical tools and guides were shared to support the skills and experiences development in the arenas of environmental impact assessments (e.g., Okala EcoDesign Guide and Strategy Wheel, C2C certification, Anastas and Warner's Green Chemistry text, etc.) and materials choice (HIGG Index, Materiom Library, Bill of Materials template, Material Safety Data Sheets, etc.).

However, fewer resource suggestions have emerged related to leadership skills, especially in the realm of interdisciplinary skills building. Tool ideas shared to support critical thinking skills development included the Seven Design Principles of the World Café, based in the Socratic Method, as well as the books *Wired to Care, Design Thinking,* and *The Art of Innovation*. Under communication skills, we were even more limited and could use more tools to buttress our collective list although suggestions were made to leverage resources created by the National Academy of Engineering (NAE).

pedagogical approaches and delivery methods

We have garnered an extensive list of potential pedagogical approaches and delivery methods to support the development of knowledge and content, skills, and experiences in ERE curricula from our past and current research efforts. We learned that these approaches transcend disciplines and will not be unique to ERE, but they were suggested and tested by engineering faculty who are experienced in teaching and integrating sustainability principles in engineering classrooms. In addition to the traditional approaches and methods common to engineering already (assigning readings, administering examinations, and giving lectures, etc.), many other less traditional alternatives were suggested to foster ERE in courses and programs. See Appendix D for the full list of recommendations.

Numerous experiential and interactive methods were provided including both short- and long-term project-based learning (PBL) approaches with specific sustainability briefs (i.e., studio and workshop-based design projects working with external partners on real products and projects, incorporating creativity and innovation activities, and joint day-long seminars where professionals and students interacted in both workshop and lecture environments). Other experiential and interactive methods suggested were interdisciplinary learning (i.e., embracing cross-functional team-based development and collaborative interactions); immersive experiences that focus on more than knowledge to include students' values and behaviors, as well as focusing on improving problem solving (using eco- , water- and carbon-footprinting exercises as well as self-reflection and assessments); partnering with companies, government, other educational institutions and/or communities; group work; discussion-based approaches; and critical reflection, assessment, and evaluations for self, paired, team, and group activities. Several games and gamification ideas were shared as a means to promote awareness of sustainability related concepts including the following approaches: sustainability-focused games (i.e., *Clime Out, FishBanks*, Snowflake Education tools and games); critique-based modules (within an existing design project); "think out loud" approach (useful with smaller groups); semi-consultant approach (direct discussions with individual lecturers); student-self teaching (i.e., swap out critique where students change roles as critiquers and experts) and role playing approaches.

Specific awareness-building methods included developing contextual awareness in students (i.e., the ability to view actions, problems, solutions, and consequences in a broader context comprising scientific, technical, economic, legal, social, or cultural aspects). It was suggested that using the following four approaches would achieve contextual awareness building: inter- and multi-disciplinary approaches, strong research connection (e.g., life-cycle research), practical education, and integrated programs. Environmental responsibility concept awareness-building approaches were also shared that fell into 5 main categories: application-based class projects (i.e., use sustainability considerations to constrain the decision space for an engineering challenge); promote holistic outlook; interdisciplinary connections and links; human behavior and motivation approaches (i.e., to foster leading sustainable livelihoods); and activities to demonstrate how engineers fit into the system. Case studies and current role models were also referenced to provide context and environmental awareness-building in engineering students.

Suggestions were made to build holistic educational ecosystems that include: curriculum integration and development, research, management, campus operations, social and cultural outreach, as well as industry support and training for industry representatives.

Several extracurricular methods were suggested including encouraging students to engage with student chapters (i.e., EWB, Netimpact, campus sustainability-groups, etc.), local communities (not necessarily sustainability-focused, social focus is important to learn things through community immersion and seeing problems firsthand), and governmental agencies to garner experience connecting with departments and doing policy work to learn about the rules that are required yet they can influence through their work. Design, business model, pitch, and entrepreneurship competitions were recommended in addition to internships, work study, and cooperative education extracurricular activities. Recommendations for other extracurricular activities involved student entrepreneurship opportunities, specialization trainings, and community support.

next steps

We will continue our work in 2019 and beyond by engaging an even larger community of stakeholders from all critical stakeholder groups with the hope that the community moves towards a list of universal principles for environmental responsibility that all engineers should be exposed to and educational outcomes that all engineers need to achieve, which we are calling the ERE framework.

If you are interested in participating in developing the ERE framework, contact the project lead, Cindy Gilbert, cgilbert@venturewell.org.

The framework would define ERE and outline key student learning outcomes. The idea is that despite the differences at each higher education institution, there are some common objectives and student outcomes that institutions can agree upon that are important for implementation within engineering programs in order to integrate environmental responsibility principles. It would serve as a collective vision and commitment.

As a collective group, we recommend the following focus areas as the next steps to advance this effort beyond this paper in order to advance the ERE education initiative through the creation of an ERE framework. Through coordinated, multi-stakeholder input, support, direction, and engagement, we will:

- Gather and summarize existing frameworks, and other relevant resources, to create an initial repository that can be shared with stakeholders and that will serve as a guide to develop the ERE framework.
- Set milestones and refine parameters for an ERE framework. Specifically, we will continue to answer these clarifying questions:
    - what is the name of this movement?
    - what is the shared vision for this work?
    - what does a system map for engineering education look like? Where are the leverage points to foster ERE?
    - what is the common definition of ERE education?
    - what are the core questions, goals, and values that define ERE education?
    - what educational outcomes will enable us to make progress?
    - what does success look like?
- Determine the best approaches to foster adoption of the ERE framework. Specifically, we will continue to answer these clarifying questions:
    - what system change needs to happen for the ERE framework to gain a foothold?
    - which of the critical stakeholder groups should we start with to cultivate adoption of the framework?
    - what is/are the most effective way(s) and communication tools to develop and employ to widely share the framework?
    - how can we foster adoption and endorsement of the framework?
    - how can we build a stronger and larger community of stakeholders?
    - what additional resources are required to support the adoption and integration of the framework?

timeline of future milestones

Below is a high-level path of critical milestones and deliverables for 2019 and for consideration in 2020 and beyond that we will strive to achieve with the collaborative support and input of our committed stakeholders.

Milestone	Projected deliverable date
Develop and grow a community of committed and inspired stakeholders	Present - January 2020
Publish initial strategy document (white paper) to VentureWell and Lemelson websites for public consumption and dialogue	July 2019
Engage stakeholder community in co-developing an ERE framework of learning outcomes and supporting resources (via webinars, surveys, etc.)	Present - December 2019
Develop strategies to unveil, share, and foster adoption and endorsement of framework	Present - December 2019
Launch, disseminate, and continue refining ERE framework	January 2020 - December 2020
Pilot change strategies to adopt framework in higher education	2020-2021
Scale change strategies in higher education and translate to K-12 grade levels	2021-2025

Table 1. High-level path forward in the development and launch of the ERE framework

a shared vision for the future engineering education

Ultimately, Lemelson and VentureWell—along with a large group of committed, engaged, and inspired stakeholders—have a shared vision to transform engineering education so that all engineers encounter the principles of environmental responsibility as an integrated part of their undergraduate education, and are equipped with the critical knowledge, skills, tools, and experiences to incorporate environmental responsibility into their future research and innovation.

Imagine a world where all products and services are created, designed, built, and distributed with the planet in mind.

Imagine a world where engineers preemptively considered and planned for all aspects of a product's life-cycle—from materials sourcing all the way to its end of life—because life-cycle thinking is completely integrated into their process from start to finish.

Imagine a world where it was natural yet prestigious for engineers to work on collaborative, transdisciplinary teams to solve humanity's most pressing problems.

Imagine a world where all engineers are environmentally responsible and considered at the vanguard of engineering professionals by industry, and those with ER skills are the most sought-after by employers.

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Appendix A:

Table of Past and Planned Future Environmentally Responsible Efforts Supported and Led by The Lemelson Foundation and VentureWell

Reference	Funder // Initiative Led By	Date
Sustainable Vision Program: workshops and grants to support social and environmental innovations	Lemelson // VentureWell	2008
Environmental Sustainability Integrated into The Lemelson Foundation's Strategy and Grant Guidelines	Lemelson // Lemelson	2012
VentureWell's Sustainable Practice Impact Award	Lemelson // VentureWell	2013
Inventing Green Workshop & RFP Issued to grantees of The Lemelson Foundation (9 different initiatives funded)	Lemelson // Lemelson	2014
Teaching Environmentally Responsible Inventing: Higher Education Environmental Landscape Research and Analysis, Phase I	Lemelson // Faludi & Gilbert	2017-2018
Follow-On Study to Allen et al., 2008 EPA Benchmarking Report: Final Report	Lemelson // Gilbert	2018
Tools for Design and Sustainability (TFDS) Online Resource Teaching Green Inventing Workshop: Integrating Environmental	VentureWell // VentureWell & Faludi	2018
Responsibility in Innovation & Entrepreneurship Education	Lemelson // Lemelson & VentureWell	2018
Sustainable Design Faculty Grant	VentureWell // VentureWell	2018
Sustainable Design Faculty Grantee Workshop	VentureWell // Faludi & Gilbert	2018
Highlights of Findings from Pre-Workshop Participant Conversations for Roundtable Event	Lemelson // Academy for Systems Change	2019
Principles of Environmentally Responsible Engineering: Creating A Roadmap for Change, Roundtable Event	Lemelson // Lemelson, VentureWell & Academy for Systems Change	2019
Snapshot of Recommended Resources from Pre-Meeting Interviews from Roundtable Event Participants	Lemelson // Academy for Systems Change & VentureWell	2019
Principles of Environmentally Responsible Engineering: 2019 Roundtable Summary and Lessons	Lemelson // VentureWell	2019
Sustainable Design Faculty Grant	VentureWell // VentureWell	2019
Initial strategy document (white paper)	Lemelson // Lemelson & VentureWell	2019
Green LaunchPad Educators Workshop	VentureWell // VentureWell	2019

Appendix B:

What do all engineering students need to know?

CONTENT/KNOWLEDGE

Why should students learn this?

What do they need to know about?

- **Systems thinking**
  - Understanding and awareness of systems outside of product or service
  - Knowledge of systems thinking practices including approaches and perspectives, that goes beyond behavioral stock and flow, and system archetypes
  - Knowledge of systems dynamics (i.e., feedback loops, system resilience, etc.)
- **Environmental and sustainability literacy**
  - Knowledge and understanding of product life cycles and life cycle thinking
  - Understanding of key environmental laws, ethics, policies, and agencies
  - Knowledge of basic facts/data about important (current/past/future) environmental issues and the motivations for working to solve environmental challenges:
    - Water and sanitation, energy, climate change, oceans and seas, urbanization and human settlements, transport, science and technology (guide posts from SDGs)
    - Pollution / toxicology / public health
    - Resource circularity / waste management / waste = food
    - Biodiversity
  - Knowledge and understanding of natural capital's two major components:
    - Abiotic natural capital comprises subsoil assets (e.g., fossil fuels, minerals, metals) and abiotic flows (e.g., wind and solar energy).
    - Biotic natural capital or ecosystem capital consists of ecosystems, which deliver a wide range of valuable services that are essential for human well-being.
  - Knowledge and understanding of key ecosystem services and functions
    - Provisioning services (e.g., production of food, water, biomass, fibre),
    - Regulating and maintenance services (e.g., soil formation and composition, pest and disease control, climate regulation)
    - Cultural services (i.e., physical, recreational, intellectual, spiritual, and symbolic interactions of humans with ecosystems, lands, and seascapes)
    - Supporting services (e.g., material cycles, energy cycles)
      - Water cycle
      - Carbon cycle
      - Nutrient cycle
      - Nitrogen cycle
      - Oxygen cycle
      - Energy cycles + types (light, chemical, etc.,)

- **Business and economic considerations**
    - Knowledge of costs and value to the environment and society beyond
    - Understanding of different business, revenue, and entrepreneurship models
    - Understanding of processes for technology to reach market adoption (i.e., technology roadmap)
- **Social implications**
    - Understanding of social impact for designs
    - Understanding of social responsibility
    - Understanding of social justice, laws, and policies
    - Ethically literate
    - Knowledge of the United Nations Sustainable Development Goals (SDGs)

SKILLS AND EXPERIENCES

What skills must all engineers have to be engineers who utilize ER best practices?
What do they need to experience and practice to lead change?

TECHNICAL SKILLS

- **Environmental impact measurement**
    - Ability to conduct life cycle assessments and analysis
    - Ability to assess broader energy implications
    - Ability to assess (environmental, health, and safety (EHS) standards (i.e., chemical hazard assessments, how to research chemical safety, etc.,)
- **Materials choice**
    - Ability to assess and select green materials (e.g., choice, flows, and circularity)
    - Ability to assess EHS aspects of materials (e.g.,: toxicity, green chemistry, etc.)
    - Ability to access and understand sustainability reporting (e.g., Global Compact (GC), GRI (global reporting initiative))
- **Design**
    - Ability to set design/engineering goals and choose strategies based on analysis
    - Ability to conduct user experience studies and social impact studies (i.e., Human-Centered Design)
    - Ability to create and employ creativity
    - Ability to visually express ideas and designs (i.e., draw, sketch, etc.)
    - Ability to design for the environment based on discipline-specific technical skills:
        - light-weighting
        - materials resourcefulness and savings
        - leverage recyclability and upcycle-ability
        - energy efficiency

LEADERSHIP SKILLS

- **Critical thinking**
    - Ability to define problems well in order to work on things that matter
    - Ability to approach and solve problems with creativity
    - Ability to conduct research
    - Ability to innovate (radical innovation vs. incremental innovation)
    - Ability to consider and make ethical and empathetic decisions
    - Ability to consider, understand, and experience different perspectives, opinions, views, etc., and to articulate varying standpoints (normative thinking)
    - Have global citizenry exposure to learn the context and importance of local, regional, national, and global perspectives
- **Communication**
    - Ability to communicate through written, graphic/visual, oral, interpersonal communication skills, in order to:
        - sell ideas
        - advocate for change and the underrepresented
        - drive organizational change
        - maximize team effectiveness
        - work well with others and across disciplines
    - Ability to lead, interact with and collaborate on cross-disciplinary teams
    - Ability to manage schedules, time, and people
- **Team work**
    - Ability to work within and function well in multidisciplinary teams
        - participates actively
        - demonstrates initiative
        - participates in group decision-making
        - shares workload
    - Ability to lead teams
        - demonstrates leadership capability
        - able to evaluate team effectiveness
        - motivates team
        - recognizes team member strengths/weaknesses
        - contributes to group effectiveness
    - Ability to display quality interpersonal skills
        - effectively communicate on teams
        - active listener and understands and incorporates different perspectives
        - is respectful
        - is empathic

Appendix C:

What are the most critical tools and guides?

KEY CONTENT, KNOWLEDGE TOOLS, AND GUIDES

SYSTEMS THINKING

- The 6 Fundamental Concepts of Systems Thinking
- Thinking in Systems
- Places to Intervene in the System
- Nature's Unifying Patterns
- AskNature.org
    - Biomole Tool
- Circular Design Guide
- Circular Strategy Cards
- Whole System Mapping
- Sustainable Minds
- Better by Design
- Design Science Lab resources
- Snowflake Education Toolkit
- Tools for Design and Sustainability (TFDS)
    - Whole Systems Mapping
    - LCA
    - Autodesk Sustainability Workshop Series videos (covered in TFDS)

ENVIRONMENTAL + SUSTAINABILITY LITERACY

- Sulitest - sustainability literacy test (based on SDGs); endorsed by Cumulus
- Story of Stuff resources - movies, teacher resources, podcast, blog
- Sustainable Development Goals (SDGs)
- Water-Energy Nexus (DOE)
- Snowflake Education Toolkit
- Zygote Quarterly

BUSINESS + ECONOMIC CONSIDERATIONS

- Strategizer for Business Model Canvas
- Business Sustainability Booster
- T-Plan - Cambridge Model (use for facilitation to get tech to market)
- NESsT I2E Inventing Green Tool
- Industry Case Studies (e.g., HP, Apple, etc.)

SOCIAL IMPLICATIONS

- Sustainable Development Goals (SDGs)
- Earth Democracy: Ten Principles of Justice, Sustainability, and Peace

KEY TECHNICAL TOOLS AND GUIDES

ENVIRONMENTAL IMPACT + LCA

- Okala Ecological Design Guide
    - Okala Educational Presentations
    - Okala EcoDesign Strategy Wheel
- Ecolizer 2.0 Ecodesign Tool
- Inventing Green: A Toolkit for Sustainable Design
- Cradle-to-Cradle Certification
- EPEAT Tool
- About Green Engineering (EPA)
- Green Chemistry
- Sandestin Declaration: 9 Principles of Green Engineering
- 12 Design Principles of Green Engineering
- A guide to reducing the environmental impact of your product
- An Engineering-to-Biology Thesaurus for Engineering Design
- Snowflake Education Toolkit
- LCA software tools (e.g., SustainableMinds, SimaPro, etc.)
- Alternative energy simulation software tools (e.g., HOMER, PVWatts Calculator, etc.)

MATERIALS CHOICE

- HIGG Index
- Design for Recycled Content Guide
- Materiom Materials Library
- Bill of Materials (BoM) Template
- Material Health Assessment Methodology
- Materiom: Nature's Recipe Book
- Materials certification programs:
    - FSC (Forest Stewardship Council)
    - PEFC (Programme for the Endorsement of Forest Certification)
    - Sustainable Agriculture Standard
- Material Safety Data Sheet (MSDS)
- EduPack - Granta Design
- Tools for Design and Sustainability (TFDS)
    - Eco-certifications
    - Green material databases
    - Autodesk Sustainability Workshop Series videos (covered in TFDS)

DESIGN

- Tools for Design and Sustainability (TFDS)
    - Eco-certifications (covered in TFDS)
    - Green material databases (covered in TFDS)
    - Autodesk Sustainability Workshop Series videos (covered in TFDS)
- Materiom: Nature's Recipe Book
- Design for Recycled Content Guide
- Nature's Unifying Patterns
- Living Principles Framework
- Design for Good

KEY LEADERSHIP TOOLS AND GUIDES

CRITICAL THINKING

- Seven Design Principles of World Cafe
- 26 Critical Thinking Skills Aligned with Bloom's Taxonomy
- The Art of Innovation
- Design Thinking
- Wired to Care
- Fundamentals for Decision Making: For Engineering Design and Systems Engineering
- Profiting from Innovation
- Case in Point
- Innovation Through Transdisciplinary Training
- Snowflake Education Toolkit
    - Tools for Dilemma Game

COMMUNICATION

- Rapid Viz
- The Elements of Style
- Technology in Services (National Academy of Engineering)
- Technology & Economics (NAE)
- Mastering a New Role: Prospering in a global economy (NAE)
- Snowflake Education Toolkit
    - Tools for Dilemma Game

TEAMWORK

- Snowflake Education Toolkit
    - Tools for Dilemma Game
- Innovation Through Transdisciplinary Training

Appendix D:

What are key pedagogical approaches and delivery methods?

Traditional methods

- readings
- examinations
- lectures

Experiential and interactive methods

- Project-based learning with specific sustainability briefs
    - studio-based design projects (short and long term)
    - workshop-based exercises (short and long term)
    - work with external partners on real products / projects (short and long term)
    - joint day-long seminars where professionals and students interacted in both workshop and lecture environments
    - creativity and innovation activities
- Interdisciplinary learning
    - cross-functional team-based development
    - transdisciplinary interactions
    - collaborative interactions
- Immersive and focus on more than knowledge to include students' values and behaviors, as well as focusing on improving problem solving
    - eco-footprint
    - carbon footprint
    - water footprint
- Partner with companies, government, other educational institutions, and/or communities
    - Group work
    - Discussion-based activities
    - Critical reflection, assessment and evaluation (self, paired, team, group)
    - Games and gamification (to promote awareness of sustainability related concepts):
        - sustainability-focused games (i.e., Snowflake Education tools and games)
        - integrating a critique-based module (within an existing design project)
        - "think out loud" approach (useful with smaller groups)
        - semi-consultant approach (direct discussions with individual lecturers)
        - student-self teaching (i.e., swap out critique where students change roles as critiquers and experts)
        - role play

Awareness-building methods

- Case studies and current role models to provide context and environmental awareness
- Contextual awareness-building (i.e., the ability to view actions, problems, solutions and consequences in a broader context comprising scientific, technical, economic, legal, social or cultural aspects).
    - interdisciplinary approach

- strong research connection (e.g., life cycle research)
- practical education
- integrated programs

• Environmental responsibility concept awareness-building
- application-based class projects (i.e., use sustainability considerations to constrain the decision space for an engineering challenge)
- promote holistic outlook
- interdisciplinary connections and links
- human behavior and motivation approaches (i.e., to foster leading sustainable livelihoods)
- activities to demonstrate how engineers fit into the system

Holistic methods

- Build holistic educational ecosystems that include:
  - curriculum integration and development
  - research
  - management
  - campus operations
  - social / cultural outreach
  - industry support and training for industry representatives

Extracurricular methods

- engage in student chapters (i.e., EWB, Netimpact, campus sustainability-groups, etc.)
- engage with local community (not necessarily sustainability-focused, social focus is important to learn things through community immersion and seeing problems firsthand)
- engage with governmental departments and policy work to learn about the rules that required that they can influence through their work
- competitions (design, business model, pitch, entrepreneurship, etc.)
- internships and work study opportunities
- entrepreneurship opportunities, training and community support

about VentureWell

VentureWell is on a mission to cultivate inventors, innovators, and entrepreneurs driven to solve the world's biggest challenges and create lasting impact. Since our inception nearly 25 years ago, we've supported and trained more than 7,500 science and technology inventors and innovators and nurtured thousands of their startups, reaching millions of people in over 50 countries with groundbreaking technological advancements in fields such as biomedicine and healthcare, energy and materials, and solutions for low-resource settings. To cultivate a pipeline of promising student inventors, we've actively supported faculty in developing programs and initiatives to transform innovation and entrepreneurship (I&E) education through grants, workshops, trainings, and conferences. To date, we've provided over $11MM in grants to faculty, which has led to the creation of more than 700 new or improved courses and programs at higher educational institutions across the country, engaging tens of thousands of students.

As a pioneering entrepreneurship support organization, VentreWell's experienced and diverse team has been on the front lines of I&E education, making deep connections and long-time partnerships with other key players and institutions within the broader I&E ecosystem. Our team was on the ground level developing and supporting the various programs, curricula, and other resources that are now standard in I&E education. This experience and vantage point provides VentureWell with a unique perspective on the ever-changing needs within the innovation and entrepreneurship ecosystem—and equips us to explore and address knowledge gaps within the entrepreneurship support community. Our organization continues to lean in to the fast-changing needs of our constituents by developing ambitious strategies and initiatives to remain nimble—and provide forward-thinking approaches for the future of innovation and entrepreneurship.

Visit venturewell.org to learn more about our organization, our work, and resources for early-stage innovators and the faculty that support them.

about The Lemelson Foundation

The Lemelson Foundation uses the power of invention to improve lives. Inspired by the belief that invention can solve many of the biggest social and economic challenges of our time, Lemelson helps the next generation of inventors and invention-based businesses to flourish. The Lemelson Foundation sees its role as a convener and collaborator in cultivating a new generation of inventors and problem solvers who view environmental responsibility as a central tenet to the design, manufacturing, distribution and disposal processes for new products and services. Together with a growing community of individuals and organizations, Lemelson is working to ensure all engineers develop the environmental stewardship skills to minimize future harm to the planet and the lives it sustains.

Established in the early 1990s by prolific inventor Jerome Lemelson and his wife Dorothy, Lemelson continues to be led by the Lemelson family. To date, grants totaling more than $210 million have been made in support of the mission.

For more information, visit www.lemelson.org.

join the initiative

If you are interested in participating in developing the ERE framework, contact the project lead, Cindy Gilbert, cgilbert@venturewell.org to learn more and to get involved.