SUPPORTING INFORMATION FOR:

Bergerson, J. A., A. Brandt, J. Cresko, M. Carbajales-Dale, H. L. MacLean, H. S. Matthews, S. McCoy, M. McManus, S. A. Miller, W. R. Morrow III, I. D. Posen, T. Seager, T. Skone, S. Sleep. 2019. Life Cycle Assessment of Emerging Technologies: Evaluation Techniques at Different Stages of Market and Technical Maturity. *Journal of Industrial Ecology.*

Summary

This supporting information includes Section 1: Acronyms and Definitions, Section 2: Alternate framings and challenges associated with quadrant system.

Section 1: Acronyms and Definitions

Emerging and Mature Markets and Technologies

As a reminder of the fundamental definitions, we consider **emerging technologies** to be those that are not produced at full-scale or –rates. Likewise, we consider a technology to be in an **emerging market** if the technology provides a novel service, or if it requires substantial market changes (e.g., infrastructure investments) before it can be deployed at scale. Table S1 defines associated acronyms used throughout the paper.

Table S1 – Acronyms and their Definitions

Acronyms	Definition
MT	Mature Technology
EM	Emerging Technology
MM	Mature Market
EM	Emerging Market
MT/MM	Mature Technology in a Mature Market (Quadrant 1)
ET/MM	Emerging Technology in a Mature Market (Quadrant 2)
MT/MM	Mature Technology in an Emerging Market (Quadrant 3)
ET/EM	Emerging Technology in an Emerging Market (Quadrant 4)

Prospective and Anticipatory LCA

This paper presents general guidance related to conducting LCA of emerging technologies without specifically weighing in on existing competing approaches. While terms have yet to be used consistently by all authors, some general distinctions can be made. There are two approaches to future-oriented (i.e., ex-ante) LCA that have become popular: 1) *prospective* and 2) *anticipatory*. Table S2 contrasts attributes of each.

The most important of these distinctions is that prospective LCA typically concerns itself with *one* technology or road map, while anticipatory LCA explores or compares several. Partly for this reason, prospective LCA is focused on forecasting, or making predictions, while anticipatory LCA is focused on exploring possibilities. Thus, the results of a prospective LCA are reported on absolute scale, and emphasized improvement assessment. By contrast, anticipatory LCA's report results on a relative scale, and are focused on comparative decision-making (e.g., Prado et al. 2017).

One of the characteristics of the anticipatory approach is that it can identify uncertainties or knowledge gaps that are most relevant to technology comparison, such that further research efforts can be directed to reducing those uncertainties that are most likely to undermine confidence in the comparison (Wender et al. 2018). With the exception of a recent illustration (Ravikumar et al. 2018), implementation of sensitivity analysis as shown in LCA literature refers to absolute measures of environmental risk or impact and thus remain ill-suited for the decision-driven approaches recommended by the National Research Council (NRC 2009). One of the disadvantages of anticipatory LCA is that normalization and weighting are not optional. Every decision analysis requires value-based trade-offs. As such, anticipatory LCA requires exploration of the context (e.g., decision alternatives under consideration) and trade-offs (e.g., López 2015; Cucurachi and Suh 2017).

Table S2: Differences between prospective and anticipatory LCA

Characteristic	Prospective LCA	Anticipatory LCA
Goal and scope	Model dependent (absolute or relative)	Comparative with an exclusion of commonalities to reduce data requirements
Scale of measure	Absolute	Relative
Uncertainty	Optional. Parameters are represented as point values or parameter uncertainty is explored through scenario or sensitivity analysis.	Explicit representation of parameter uncertainty as probability distributions with Monte Carlo sampling, for purpose of characterizing confidence in comparison.
Normalization	Optional, external, and fully compensatory.	Compulsory, internal, and partially compensatory.
Weighting	Optional. Represented as point estimates, where multiple weight vectors represent comparative scenarios.	Compulsory. Represented as bounded probability distributions (e.g., uniformly distributed between minimum and maximum constraints).
Sensitivity analysis	Local or global sensitivity analysis prioritizing uncertainties for hotspot improvement.	Global sensitivity analysis to prioritize uncertainties for improving decision confidence in the choice of an emerging technology alternative.

Characteristic	Prospective LCA	Anticipatory LCA
Reporting of results	Model dependent. Maybe prescriptive or descriptive.	Prescriptive with a focus on decreasing the uncertainty in the choice of the technology alternative. Includes environmental values of the stakeholders.

Section 2: Alternate framings and challenges associated with quadrant system

The quadrant system presented in the main text endeavors to adhere to the old adage that everything should be made as simple as possible, but not simpler. Throughout a year of discussion among the authors of this paper, and with participants of conference special sessions, a number of other dimensions to the quadrant system were considered and ultimately rejected – not due to their lack of utility, but rather due to the complications they introduced to the quadrant system presented in the paper. This section documents some of those conversations, and addresses a subset of additional aspects that were lost from the main presentation.

The meaning of the bubbles and their overlap

The technology and market 'bubbles' presented in Figure 2 calls attention to the overlap between technology and market factors and illustrates how the magnitude of uncertainty associated with these factors varies depending on the quadrant of the associated technology. Figure S1 presents the factors that affect uncertainty within the technology and market spheres as well as factors that factors that exist in the space where technology and market spheres overlap.

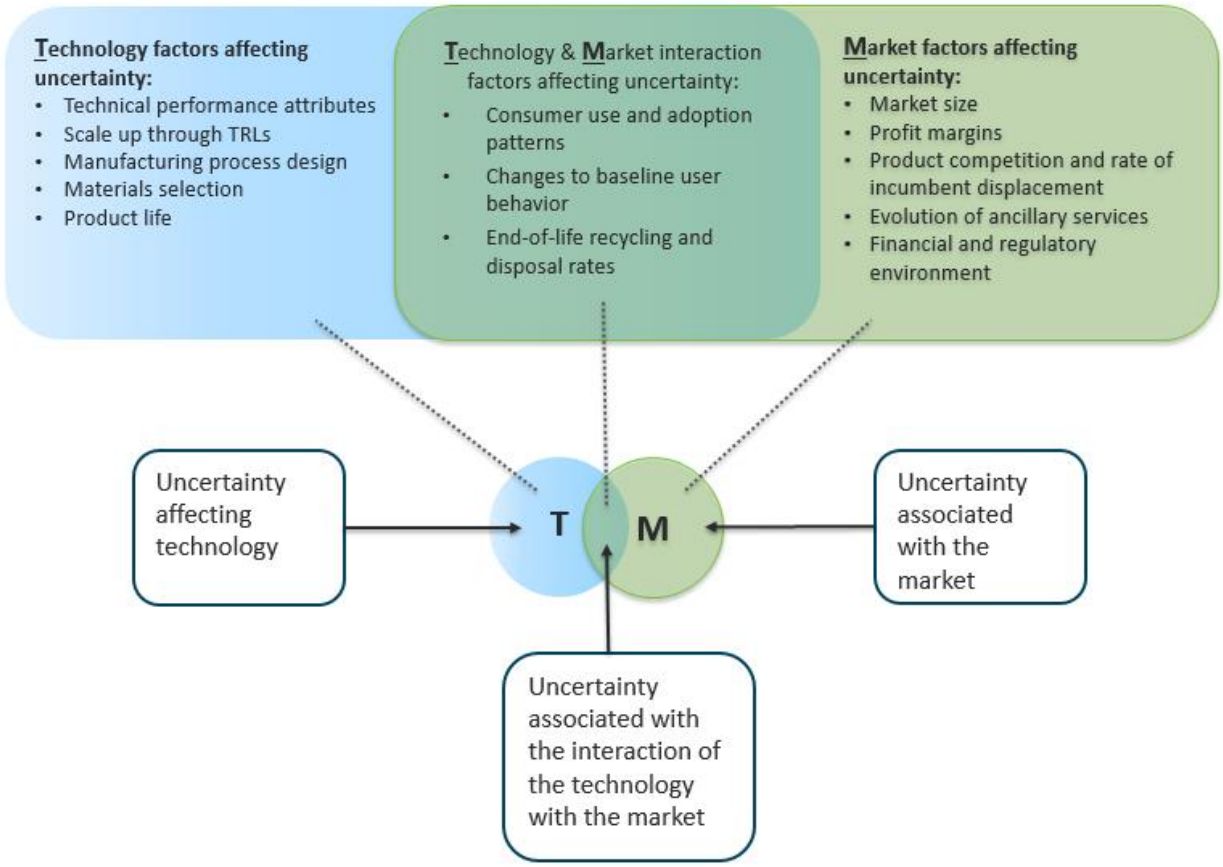

Figure S1. Uncertainty associated with technology and market aspects of the emerging technology system, including uncertainty associated with technology/market interactions

Regarding bubble size presented in Figure 2, the exact meaning of the size and degree of overlap between these bubbles was the subject of considerable debate and has been left somewhat open ended to allow for different interpretations. Each interpretation enables different insights that complement the quadrant system presented in the main text. The uncertainty associated with technology and market factors has two key dimensions: uncertainty of the parameter itself, and importance of that uncertainty for the future system and associated LCA results. The confluence of the two can produce a lensing effect, via which the size of the bubble dictates the range of plausible futures, as illustrated in Figure S2. As more information is gathered, or new decisions are made (i.e., as the technology matures), the associated market and technology bubbles shrink, leading to a narrower set of possible futures.

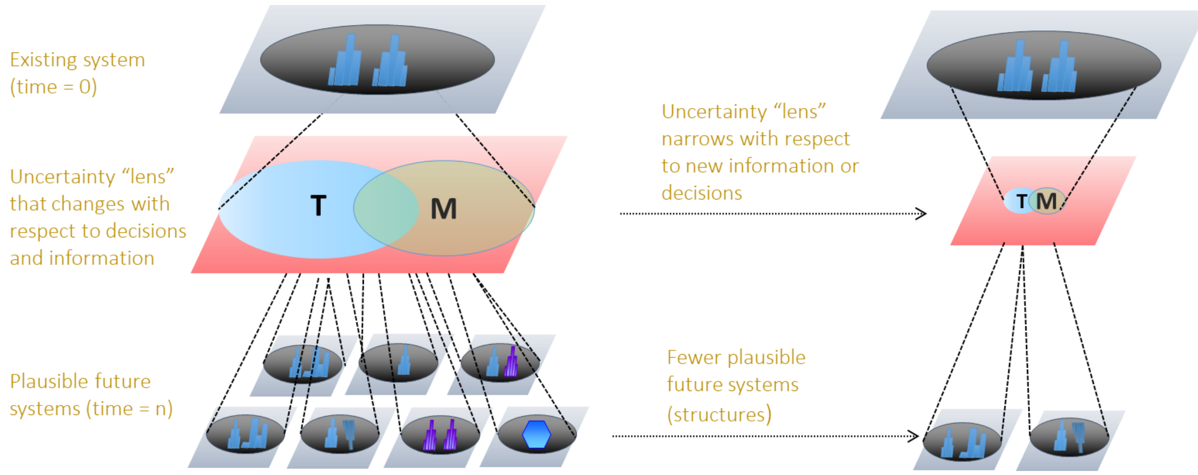

Figure S2. Representation of technology and market factors as lenses through which plausible futures can be constructed from the current system. The size of the bubble represents the degree to which that parameter contributes to uncertainty in the future system.

As a result of the different dimensions of uncertainty, there are fundamental questions about what exactly the bubbles mean, and as a corollary, how does one interpret the overlap between them. Some useful alternate interpretations are outlined as follows:

i. The bubbles represent what aspects of the existing system are influenced by the new technology. In that regard, the overlap between bubbles represents domains in which the factors can influence one another. For example, battery choice in an electric vehicle is a strictly technological parameter but may influence use patterns and penetration (market factors) via its impact on vehicle range. Likewise, vehicle fuel consumption is usually considered a technological parameter, but can in turn be influenced by how the vehicle is driven (a market parameter). Such interactions are often important for the final LCA result.
ii. The bubbles represent degree to which the overlap represents an area where the two domains have joint (non-additive) effects on the LCA results. (e.g., efficiency for an electricity-using product is a technology characteristic, but the resulting impact will depend on geographic adoption patterns – e.g., due to heterogeneity in climate and electric grids). Thus, even if technology and market factors do not influence one another (as in interpretation 'i'), their effect on LCA results can only be felt jointly. Although overlap is likely to be common, some technology parameters (e.g., direct process emissions) are likely independent of market factors, while some market parameters (e.g., Drabik and de Gorter 2011) may depend only on the market structure and incumbent technology, rather than on technological characteristics of the new product.

An additional 'structure' or 'system' bubbles?

The evolution of both background and foreground systems is key to evaluation of emerging technologies. Early iterations of the quadrant system explicitly included 'structure' and 'system' bubbles which can be defined as follows:

(i) **System** is where the impact of a technology in a market occurs, and where the effects of technology/market uptake are observed. It is inclusive of all elements within the system boundaries of the analysis. In this definition, the technology and market bubbles are embedded in a wider structural bubble (e.g., see pink rectangle in Figure S2), calling attention to where exactly changes are taking place.

(ii) **Structure** is a set of parameters that are determined independently of the technology design and deployment, but affect the environmental impacts of the technology nevertheless. Examples include installed infrastructure, intensity of the electricity grid, and the regulatory environment. This version of a 'structure' bubble explicitly calls attention to background systems which are independent of the technology being studied, but which nonetheless influence LCA results. In this conception, 'structure' creates a third dimension of uncertainty (related to the future of background systems), which is plausibly exogenous to the product under study, and which does not necessarily shrink as the technology matures (see Figure S3)

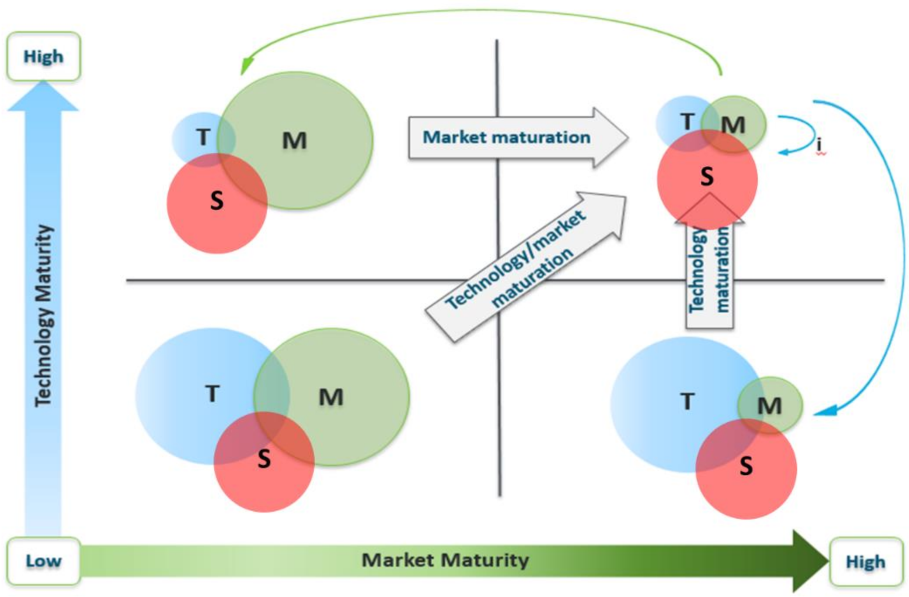

Figure S3. An alternate conception of Figure 4, with an additional "structure" bubble.

Although there is an important conceptual distinction between foreground and background systems in LCA, the main text opts to include all such market parameters within the single 'market' bubble, both for simplicity and for consistency with the two-dimensional axis system (technology/market) we define.

The need for additional temporal and scale dimensions

The potential uncertainty associated with the evolution of background systems (discussed above), calls attention to two key dimensions of emerging technologies that are not (yet) treated in the proposed quadrant system: time and scale/rate of production. A sketch of how time and production rate may interact with our proposed quadrant system is shown in Figure S4. Technologies mature over time, and with increasing scale of production, with regular potential for the introduction of new competing technologies. For short time horizons and small production scales, substantial reorganization of the 'market' is unlikely, reducing market uncertainty even for technologies that would be considered to be within markets with low levels of maturity. Likewise, the degree to which technological improvements can be expected will also depend on the time horizon considered and rate of improvement, along with the scale of production – especially if 'learning by doing' is expected to be a factor. As a result, the time horizon for analysis and the expected scale of production are key considerations that will influence both the relative dominance of technological vs market maturity, as well as the appropriate analyses to include within LCA studies. A more detailed integration of these concepts is left as future work.

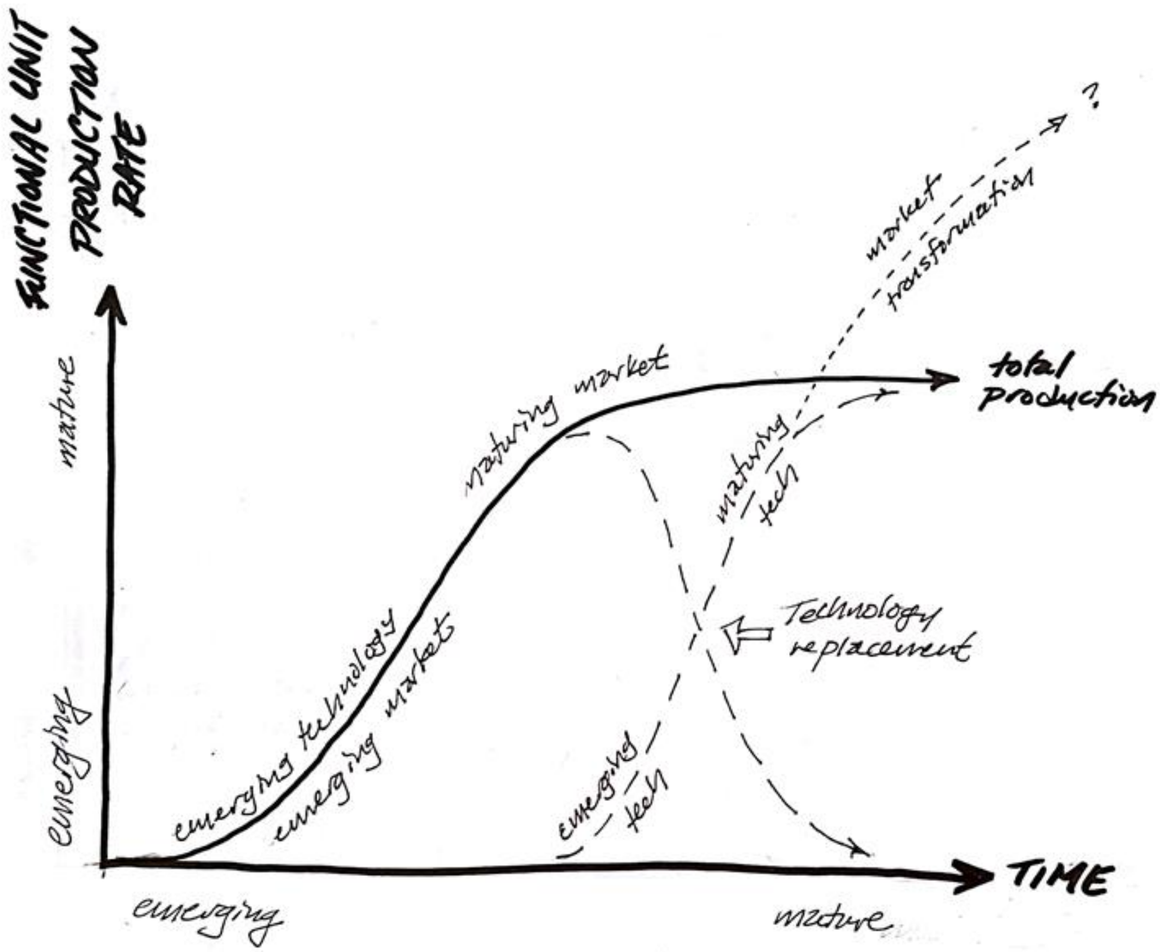

Figure S4.Hypothetical diagram showing interaction between technological/market maturity and time/scale of production.

The difficulty of placing technologies within a quadrant

As suggested by Figure 2 in the main text, technologies regularly move between quadrants, posing difficulties for an LCA practitioner to associate their analysis squarely within a single quadrant. In addition to the time period and scale of production considered, other factors such as the functional unit of analysis can affect the maturity of a technology. To illustrate this difficulty, we consider a few specific examples.

Battery Electric Vehicles: In special session workshops in which our quadrant system was discussed, Battery Electric Vehicles (BEVs) were often placed at the very center of the four-quadrant system. Electric vehicles are already produced at scale, and the market for passenger vehicles is well established. However, BEVs do not offer exactly the same service as conventional vehicles (e.g., due to limitations in range and charging infrastructure), and may yet see substantial changes in key component technologies (e.g., related to choice of battery). Thus, placing BEVs on the quadrant system may vary depending on the functional unit considered, as well as the scale of penetration and exact technological parameters considered.

Desalination technology: Large-scale desalination is arguably a mature technology, but which has yet to be deployed in in the United States. This was initially discussed as a potential example of a mature technology (already deployed in other regions of the world) in an emerging market (not previously used at scale in the United States). Nevertheless, there is a clear pre-existing market for clean water, and so it is questionable whether the market may truly be considered emerging despite the new context for the technology. If it is to become a primary water source within the United States, however, substantial redesign of current water distribution networks may be required. Thus, again, placement of this technology within the quadrant system may depend on the scale and context of its deployment.

Biofuels: Biofuels represent a large category of technologies that were raised as potential examples throughout multiple iterations of this paper. At low blend levels, fuels like ethanol (used in gasoline) and biodiesel (used in conjunction with petroleum diesel) are generally compatible with existing infrastructure, but require more structural changes at high levels of use. So, are these fuels currently entering emerging or mature markets? Likewise, how does one classify technologies that are well understood and can produce drop-in fuels (e.g., the Fischer Tropsch process) but are not currently deployed at scale? If a process (e.g., for the production of lignocellulosic biofuel) is established but requires fundamental changes (e.g., for cost reduction) to enjoy greater market penetration, is that technology mature or emerging? These questions illustrate some of the difficulties with which the authors have contended while developing the proposed quadrant system.

ACLCA Special Session Abstracts: a history of discussing the challenges associated LCA of Emerging Technology

ACLCA Conference Special Sessions on Emerging Technologies:

1. LCAXVIII (2018) Special Session: "*LCA of Emerging Technologies: Open Discussion of Analysis Framework Developments"*
2. LCAXVII (2017) Special Session: "*Towards a framework for LCA of emerging technologies*"
3. LCAXVI (2016) Special Session: "*Prospective LCA to Understand Energy Impacts of Manufacturing Across the U.S. Economy*"
4. LCAXV (2015) Special Session: "*Cultivating uniform methods for prospective LCA of emerging technologies – A Round Table Discussion*
5. LCA XIV (2014) "*Life Cycle Energy Analytical Framework for Advanced Manufacturing – an Efficient Materials and Industry Energies Future"*

LCAXVIII (2018) Special Session: "*LCA of Emerging Technologies: Open Discussion of Analysis Framework Developments"*

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Abstract Summary:

The growing interest in applying LCA methods to guide early-stage technology development highlights the necessity to continue developing appropriate methodologies and tools. As identified and discussed during LCA XVII's Special Sessions "Towards a framework for LCA of emerging technologies", existing LCA guidelines (suited for evaluating commercially established products or processes) are not well defined and have practical and methodological difficulties if applied to emerging technologies due to the prospective nature of forecast. During last year's session existing methodological issues were identified, discussed to creatively develop build consensus around how to address them through audience participation. The special session will continue the creative discussion format through example topics, questions, and recently evolved methodology frameworks. This special session should complement the special session proposal titled "Emerging, Disruptive and Converging Technologies: Methodological challenges and Modelling opportunities in LCA."

We will facilitate high level discussion on the need for uniformity, consistency, and robustness when assessing emerging and advanced technology adoption potential by encouraging audience dialog. We propose a general topic ("the Connected Economy") in order to openly discuss the wide range of affects and life-cycle implications of technologies poised for economy-wide shifts in social and environmental systems.

PURPOSE:

Engage in a dialogue around how to effectively apply prospective LCA to evaluate emerging technologies and the impacts on economy-wide energy systems.

OUTCOMES:

Attendees will hear about how prospective LCA has been used and efforts to incorporate technology adoption into the analyses. Attendees will be invited to contribute to the body of knowledge and help inform future efforts around prospective LCA. The growing interest in applying LCA methods to guide early-stage (AKA "emerging") technology development has motivated our efforts to establish LCA methodologies and tools that are appropriate for anticipating future impacts. During our LCAXVII Special Session: "Towards a framework for LCA of emerging technologies", we presented a theoretical hypothesis that the future impacts are As identified and discussed during the prior ACLCA conference Special Session on Emerging Technologies (See list below, existing LCA guidelines (suited for evaluating commercially established products or processes) have practical and methodological difficulties if applied to emerging technologies. During our LCA XVII session, we hypothesized that an appropriate LCA methodology for Emerging Technology should include the technology adopting markets and their state of maturity. Given this hypothesis, we elicited audience participation to discuss and identify issues and how to address them.

This special session will continue the collaborative and creative discussion format through example topics, questions, and recently evolved methodology frameworks. We will facilitate high level discussion, encouraging audience dialog, on the need and approaches for uniformity, consistency, and robustness when assessing emerging and advanced technology adoption potential. We propose a general topic ("the Connected Economy") in order to openly discuss and debate the wide range of life-cycle implications of technologies poised for economy-wide shifts in social and environmental systems. The "Connected Economy" topic in the session will tie to a separate abstract focused on the author's current "Connected Economy" LCA work.

LCAXVII (2017) Special Session: "*Towards a framework for LCA of emerging technologies*"

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Abstract Summary:

To tackle societal grand challenges, technology developers and engineers must simultaneously maximize economic benefits while minimizing environmental risks and impacts associated with processes, products or services. The Department of Energy is increasingly relying on both techno-economic analysis (TEA) and life cycle assessment (LCA) as additional information to be submitted within proposed projects (e.g. the recent MEGABIOS and ABY2 FOAs), even for research at very early-stage development (e.g. technology readiness level, TRL, 3 or 4). Being able to use LCA within the laboratory stage (TRL2-5) could provide guidance for technology developers to greatly minimize environmental impacts. Existing LCA guidelines are well suited to evaluate products or processes that are already commercially established. However, tools appropriate for prospective assessment of early-stage technologies are not well defined and have practical and methodological difficulties.

This special session will explore recent methodological advances in prospective LCA for early-stage (low technology readiness) technologies, identify existing methodological issues and attempt to build consensus around how to address them. The session will present the need for such a framework and output from a recent 2-day workshop on the topic held in Banff, Canada.

PURPOSE:

Engage in a dialogue around how to effectively apply prospective LCA to evaluate emerging technologies and the impacts on economy-wide energy systems.

OUTCOMES:

Attendees will hear about how prospective LCA has been used and efforts to incorporate technology adoption into the analyses. Attendees will be invited to contribute to the body of knowledge and help inform future efforts around prospective LCA.

LCAXVI (2016) Special Session: "Prospective LCA to Understand Energy Impacts of Manufacturing Across the U.S. Economy"

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Abstract Summary:

New materials and process technologies directly impact not only the energy and emissions footprint of the manufacturing sector but also have economy wide impacts resulting from the adoption and use of those manufactured products. Prospective LCA can capture the impacts of next generation technologies and products. This session examines these prospective impacts, and can help identify opportunities for improvements in energy and materials utilization. The analysis covers the system from the following levels:

- Individual manufacturing processes and unit operations
- Goods-producing facilities, including manufacturing business processes
- Manufacturing supply chains and manufactured goods, including impacts from all phases of the product life cycle

In this session, our framework will be described, and the analysis will be illustrated in three examples.

PURPOSE:

Engage in a dialogue around how to effectively apply prospective LCA to evaluate emerging technologies and the impacts on economy-wide energy systems.

OUTCOMES:

Attendees will hear about how prospective energy LCA has been used in the DOE Quadrennial Technology Review and other AMO projects, and efforts to incorporate technology adoption into the analyses. Attendees will be invited to contribute to the body of knowledge and help inform future efforts around prospective LCA.

LCAXV (2015) Special Session: "Cultivating uniform methods for prospective LCA of emerging technologies – A Round Table Discussion"

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Arman Shehabi, Lawrence Berkeley National Laboratory

Special Session (90 minutes) format:

1. Introduction (30 minutes) – high level discussion on the need for uniformity, consistency, and robustness when assessing emerging and advanced technology adoption potential.
2. Round-Table Discussion (60 Minutes) – how industry organizations are developing or applying uniform, consistent, and robust energy LCA to inform technology development

Special Session Abstract:

The growing application of Life-Cycle Analysis (LCA) for emerging technologies is a promising strategy to help guide innovation towards a more sustainable future. However, anticipating the future is inherently uncertain and emerging technologies can cover a wide range of opportunities. Increasingly, R&D researchers are asked to estimate future benefits from emerging technologies in addition to performing technology R&D. In the absence of a uniform method and guidelines, prospective LCA may yield inconsistent estimates, making it difficult to verify or compare results between similar technologies or across a wide range of technology categories. Prospective LCA of emerging technologies will benefit from uniform, consistent, and robust frameworks for estimating future impacts.

In this special session, we will start with a high level discussion on the need for uniformity, consistency, and robustness when assessing emerging and advanced technology adoption potential (Proposed 30 minutes). We will briefly discuss our efforts to develop transparent and verifiable LCA methods, and its use in evaluating technologies. This will lead into a round-table discussion of prospective LCA methods that can be applicable to emerging technologies covering a wide range of industrial technology areas ((Proposed 60 minutes).

The round-table discussion will include the panel participants listed below to discuss how their organizations are developing or applying uniform, consistent, and robust energy LCA to inform technology development. The round-table discussion will seek to highlight the pros and cons of applying prospective LCA to advanced and emerging technologies, with a sharp focus on considerations leading to consistent and verifiable results.

Round-Table Panel Discussion Participants

Joe Cresko, Advance Manufacturing Office, EERE, DOE
Bill Flanagan or Angela Fisher, GE
Timothy Gutowski, MIT
Rich Helling, Dow Chemicals
Noorie Rajvanshi, Siemens

LCA XIV (2014) "Life Cycle Energy Analytical Framework for Advanced Manufacturing – an Efficient Materials and Industry Energies Future"

Special Session Format: individual presentations (60 minutes) followed by a round table discussion (30 minutes)

Presenters and panel members:

Joe Cresko, Advance Manufacturing Office, EERE, DOE
Alberta Carpenter, National Renewable Energy Laboratory
William R. Morrow III, Lawrence Berkeley National Laboratory
Sachin Nimbalkar, Oak Ridge National Laboratory
Sujit Das, Oak Ridge National Laboratory
Eric Masanet, Argonne National Laboratory and Northwestern University

Special session description:

The Office of Energy Efficiency & Renewable Energy (EERE) leads the U.S. Department of Energy's (DOE) efforts to develop and deliver clean, market-driven, energy-saving solutions for industries, buildings, transportation, and electricity generation. Manufacturing can leverage energy savings across all sectors of the U.S. economy and clean energy manufacturing can reduce the environmental impact in the making, use, and end-of-life of manufactured products. EERE's Advanced Manufacturing Office (AMO) funds the research, development, and demonstration (RD&D) of highly efficient and innovative technologies that: a) improve industry's energy intensity and production; b) can spur scale adequate to prove their value to manufacturers and drive investment; and c) produce products that use less energy throughout their life cycles. This requires a uniform prospective life-cycle assessment (LCA) approach with the capability to analyze adoption and deployment scenarios has been developed to estimate potential manufacturing and life-cycle impacts of a wide range of future advanced manufacturing technologies. This special session presents two foundational methods and associated tools as well as an additional complementary tool for specific technology analysis based on a collaborative effort across multiple DOE laboratories (ORNL, ANL, LBNL, and NREL) to undertake economy-wide energy analysis.

- **The Materials Flows through Industry (MFI)** – an input-output process based approach that estimates the embodied energy of specific industrial materials through the supply chain. The tool has several options to narrow down the assessment and to evaluate alternative scenarios (such as efficiency improvements, process changes, or materials substitution).
- **The Lifecycle Industry GreenHouse gas, Technology and Energy through the Use Phase (LIGHTEnUP)** – provides an energy assessment of future technology implementation and adoption scenarios through multiple sectors of the U.S. economy, based on government data sets for industrial, buildings, and transportation energy use and projections.
- **The Additive Manufacturing Energy Impacts Assessment (AM) tool** – a targeted life cycle analysis tool that allows for the evaluation of different additive manufacturing processes (aka 3-D printing, an emergent advanced manufacturing technology) at varying levels of detail.

This special session will provide an overview of these foundational methods and tools, and provide some case study examples of advanced lightweight materials for transport vehicles. In particular, we will stress how a robust assessment of cross-sector impacts requires a thorough understanding of each of the life cycle phases, and demonstrate and discuss how the manufacturing phase can be particularly challenging to model for emerging technologies.

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