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PERSPECTIVE

Anticipatory life-cycle assessment for responsible research and innovation

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The goal of guiding innovation toward beneficial social and environmental outcomes – referred to in the growing literature as responsible research and innovation (RRI) – is intuitively worthwhile but lacks practicable tools for implementation. One potentially useful tool is life-cycle assessment (LCA), which is a comprehensive framework used to evaluate the environmental impacts of products, processes, and technologies. However, LCA ineffectively promotes RRI for at least two reasons: (1) Codified approaches to LCA are largely retrospective, relying heavily on data collected from mature industries with existing supply chains and (2) LCA underemphasizes the importance of stakeholder engagement to inform critical modeling decisions which diminishes the social credibility and relevance of results. LCA researchers have made piecemeal advances that address these shortcomings, yet there is no consensus regarding how to advance LCA to support RRI of emerging technologies. This paper advocates for development of *anticipatory* LCA as non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with an emerging technology. By identifying the most relevant uncertainties and engaging research and development decision-makers, such anticipatory methods can generate alternative research agenda and provide a practicable tool to promote environmental RRI.

Keywords: anticipation; technology assessment; foresight; knowledge integration

1. Introduction

Potential environmental impacts of emerging technologies are often only identified, regulated, and mitigated *after* large-scale production and dissemination (Davies 2009). Early research and development (R&D) suffers from a lack of integration of environmental research. This is problematic for at least three reasons: (1) many of the environmental impacts caused by a technology become locked in by R&D decisions (Bhander, Hauschild, and McAloone 2003); (2) in the early phases of technology development there exists greater flexibility for environmental considerations to guide the innovation process (Stilgoe, Owen, and Macnaghten 2013); and (3) the separation of environmental research from technology development positions assessment and regulation as retrospective and reactive (Owen and Goldberg 2010). An alternative model is to integrate broader criteria into technology development (Fisher and Rip 2013). Rather than rely

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on retrospective approaches, design criteria explicitly drawn from social and environmental values can structure more effective interventions in the nascent stages of technology development, and thereby promote responsible research and innovation (RRI) practices (Owen, Baxter, and Depledge 2009). However, there is a paucity of practicable design tools that effectively integrate broader values into technology R&D. This paper argues for the development of *anticipatory* life-cycle assessment (LCA) methods as one tool to promote integration of environmental criteria early in the stage-gate innovation model and support the broader goals of RRI. Anticipatory LCA will be a collection of best practices from existing prospective studies as well as new methods, codified into a single, cohesive, easy-to-follow methodology.

2. LCA and its discontents

LCA – a comprehensive framework for evaluating environmental impacts of processes, products, or technologies – is the preferred analytic framework for environmental assessment because the broad boundaries used prevent the shifting of environmental burdens from one life-cycle phase or environmental compartment to another. For example, the rapid growth in production of corn-derived ethanol was partially justified by amelioration of greenhouse gas emissions. However, the narrow policy focus on mitigation of climate change came at the expense of increased eutrophication impacts – a trade-off easily identified by LCA (Miller, Landis, and Theis 2006).

To reduce the likelihood of unintended environmental consequences, research policy organizations increasingly recommend application of LCA to emerging technologies (NRC 2012). Implicit in such calls is a desire to foster environmental RRI by identifying potential impacts before commercial-scale production and technology diffusion. However, traditional approaches to environmental LCA ineffectively promote RRI of emerging technologies for at least two reasons: (1) Codified practices rely extensively on data collected from mature industries with existing supply chains and are thereby largely retrospective and (2) Established practices under-emphasize the importance (and oversimplify the process) of stakeholder engagement in shaping LCA models and results, and thereby suffer diminished social credibility and relevance. Regarding the first point, there has been isolated progress in advancing LCA methods toward prospective identification and mitigation of environmental impacts, yet these tools have not been integrated into a comprehensive framework that supports RRI of emerging technologies. Regarding the second point, this manuscript emphasizes the importance of inclusion of diverse stakeholder values in critical environmental LCA modeling decisions, which may identify a need to generate multiple LCA models based on what values are included. Overcoming these barriers builds capacity for LCA to engage R&D decision-makers with broader environmental values and provides a tool that contributes to environmental RRI of emerging technologies.

3. From retrospective to prospective LCA

Most LCA applications are retrospective in that they occur after commercial-scale production by large businesses and distribution to consumers according to laws set by regulatory agencies. Such analyses are useful for informing consumers and regulators about the environmental impacts of a product (e.g. carbon footprints and eco-labeling), yet have limited ability to reorient technology trajectory because temporal delays and large capital investments contribute to technology lock-in (Collingridge 1980). Qualitative approaches such as life-cycle thinking (Thabrew, Wiek, and Ries 2009) can provide useful heuristics early in R&D but lack the quantitative rigor of LCA. To address this shortcoming, a growing literature of *prospective* LCA employs modeling tools that require less accurate data sets and focus analyses on potential environmental impacts arising from R&D decisions. Drawing from diverse fields ranging from future studies to thermodynamics, published advances include incorporation of backcasting (Herwich 2005), foresight tools, and scenario development into LCA and material-flow analysis (Pesonen et al. 2000; Spielmann et al. 2004; Wender and Seager 2011; Eckelman et al. 2012; Dale et al. 2013; Simon and Weil 2013; Zimmermann et al. 2013), dynamic LCA process modeling (Collinge et al. 2013), thermodynamic modeling of manufacturing processes (Gutowski et al. 2009; Gutowski, Liow, and Sekulic 2010), and stochastic decision analysis (Canis, Linkov, and Seager 2010; Linkov et al. 2011; Prado-Lopez et al. 2014). These tools advance LCA methods and call attention to potential future environmental impacts of emerging technologies while early in R&D.

4. Integrating societal values

Application of LCA early in R&D is insufficient to promote environmental RRI if societal values are not integrated and alternative perspectives explored. Critiques of LCA identify long-standing challenges in recognizing where and how to incorporate stakeholder value preferences into environmentally focused analysis (Berube 2013), which increases the social credibility and relevance of LCA results. Inclusion of stakeholder values in environmental LCA is distinct from the rapidly expanding field of social life-cycle assessment (S-LCA), which quantifies burdens in defined social impact categories such as child labor and indigenous rights (UNEP 2013) or life-cycle sustainability assessment (LCSA) (Guinee et al. 2011), which entails concurrent application of LCA, S-LCA, and life-cycle costing to identify environmental, social, and economic impacts, respectively. While S-LCA and LCSA have a broader scope than environmental LCA and are designed to explicitly represent social impacts, these tools may suffer from a similar lack of stakeholder engagement to guide model construction.

While stakeholder engagement is discussed in ISO standards for environmental LCA, practitioners typically do not have the requisite training to identify affected parties and elicit the relevant value preferences. There are numerous decisions in environmental LCA that are normative, including: (1) system boundary definition (what activities are included), (2) functional unit selection (what service the technology provides), (3) impact category selection (what environmental impacts are considered), and (4) weighting (to what extent impacts in one category matter relative to another). As opposed to a practitioner making these decisions in isolation, environmental LCA should employ social science engagement methods to identify impacted stakeholders, elicit their value preferences, and use these numerous – often conflicting – perspectives to inform modeling decisions.

Explicit statement and inclusion of these values may result in several model configurations (e.g. multiple system boundaries or functional units based on what stakeholder values are represented). The process should be iterative and reflexive – for example, system boundary definition influences initial stakeholder identification, what activities are included, and how benefits and impacts are distributed. Conversely, a detailed secondary stakeholder analysis may reveal the need to redefine system boundaries. Rather than ignoring stakeholder differences in an attempt to be unbiased, LCA should explicitly account for these values and biases and provide a tool to quantitatively explore alternative perspectives to complement value-sensitive design (Taebi et al. 2014).

5. Toward anticipatory LCA for responsible research and innovation

There is an opportunity to remake LCA as a tool to guide environmentally responsible product innovation by building on prospective modeling advances and exploring multiple configurations of system boundaries, functional units, impact categories, and weights based on modeled stakeholder values. The goal is to create a tool that integrates environmental concerns into the technology development process in a way that anticipates foreseeable negative consequences, identifies opportunities for improving the environmental profile of emerging technologies, and communicates findings to R&D decision-makers in time to reorient research. With this objective, we build upon advances in the domain of anticipatory governance (Guston 2013) – borrowing the terminology to define *anticipatory* LCA as a forward-looking, non-predictive tool that increases model uncertainty through inclusion of prospective modeling tools and multiple social perspectives. As opposed to prospective LCA, which treats uncertainty largely as a measure of model reliability, anticipatory LCA should not seek to create a realistic model but rather to expand uncertainty and perform global sensitivity analysis to identify the most environmentally promising research agendas. In this capacity, anticipatory LCA may generate many models all with a high degree of uncertainty in order to explore a broad spectrum of possible futures (as opposed to a select few, most likely) to build capacity to prepare for many potential outcomes. Using anticipatory LCA as a tool not to predict the future, but to prepare for it, provides one approach to contribute to the broader goals of RRI.

Figure 1 illustrates a sequential stage-gate model of increasing market readiness that product innovations typically progress through (Robinson 2009), compares intervention points for retrospective and anticipatory LCA, and lists relevant actors associated with each stage. In early R&D activities (bench-scale and prototyping phase), technology developers and research funders from both industry and academia begin to assess the technical performance and financial returns on investment characteristics of the technology (Foley and Wiek 2013). Gates (dotted lines on Figure 1) open and product development proceeds only when specific objectives – typically technical, financial, and legal – are met.

The stage-gate model of product innovation is criticized for considering only technical and economic criteria during laboratory-scale research and prototyping activities, whereas broader

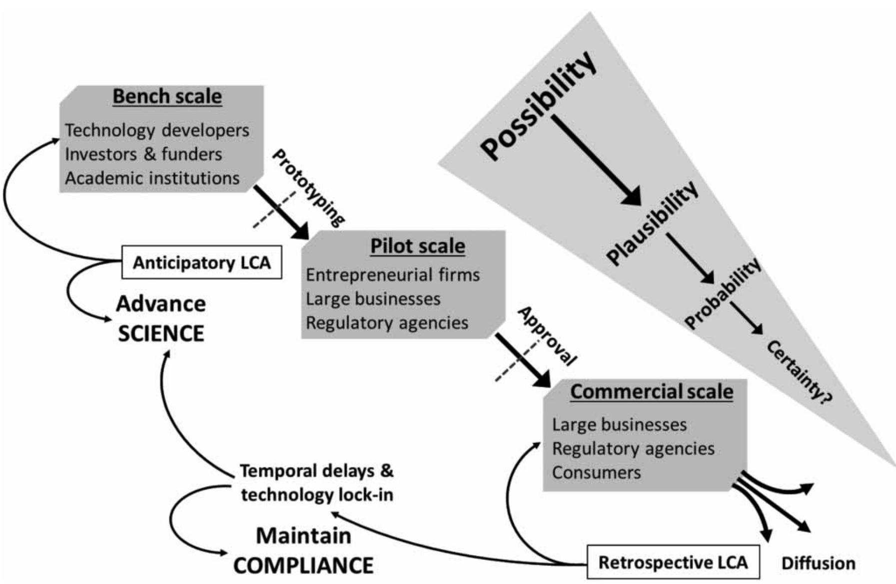

Figure 1. Intervention points of retrospective and anticipatory LCA in technology development.
Note: Applying LCA earlier in stage-gate innovation overcomes temporal delays and technology lock-in limiting retrospective LCA, and thereby has greater potential to reorient technology development through integration of broader criteria into bench-scale research.

socio-environmental impacts (albeit highly uncertain) occur in later stages, if at all (Stilgoe, Owen, and Macnaghten 2013). Applying LCA after commercial production and diffusion – termed retrospective LCA – filters out unacceptable technologies and serves as a tool to maintain compliance. Alternatively, anticipatory LCA should seek to provide broader environmental criteria early in R&D to promote formulation of new research agenda, and in doing so become a tool that advances science.

The proposed design and assessment tool is not the singular solution to achieve RRI, and significant work remains to develop generalizable methods for anticipatory LCA. Nonetheless, as discussed here, it adds reflexivity earlier into the product innovation process, integrates knowledge from disparate disciplines, is inclusive of broader societal values, and anticipates foreseeable future implications. While not all impacts can be identified or avoided, when implemented in an adaptive approach that leverages continuous learning this tool can aid in reducing negative environmental impacts. In this way anticipatory LCA embodies the core principals of RRI outlined by Stilgoe, Owen, and Macnaghten (2013) and aligns normative goals regarding socio-ecological impacts with von Schomberg's notion of 'acceptability, sustainability and societal desirability' (2013, 64). A diversity of researchers, government agencies, and private organizations can participate in moving this research agenda forward.

6. Who can use anticipatory LCA?

Anticipatory LCA requires further attention and development as a practicable design tool used to implement environmental RRI into R&D processes. It provides a conceptual model to structure knowledge communication and collaboration between numerous stakeholders and a wide range of actors involved in innovation. *Research funders* could apply anticipatory LCA to systematically and quantitatively generate scenarios of potential impacts arising from alternative investment strategies. As the technology remains in a formative stage of development scenarios can overcome temporal delays by assessing future, broader impacts. This information complements economic and technical metrics to prioritize investment strategies that maximize positive social and environmental outcomes. Physical scientists, engineers, and other technology developers could apply anticipatory LCA to explore potential broader impacts associated with their laboratory research decisions, and could be engaged in structuring R&D activities that are responsive to social and environmental concerns. As a design tool, anticipatory LCA could provide timely feedback to technology developers and inform initial material selection, energy targets, end-of-life management strategies, maintenance options, and user demands. Social scientists who engage diverse stakeholders and explore the societal implications of emerging technologies could employ anticipatory LCA as a tool with increased technical detail than other foresight methods. Furthermore, this tool could provide an opportunity to integrate social scientists with environmental and technical researchers while yielding holistic metrics of technology trajectories and communicating findings to research funders. Environmental researchers can use anticipatory LCA to prioritize experimental research that will lead to the greatest reductions in uncertainty and most environmental improvement across the life cycle of emerging technologies. Together, these activities engage a broad spectrum of actors in innovation processes and can contribute to environmental RRI.

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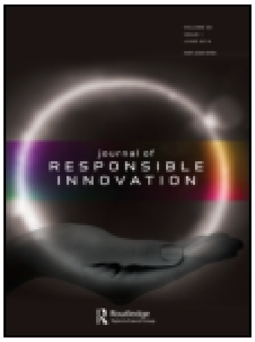

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