Systems & Control Transactions

Research Article
Foundations of Computer Aided Process Design (FOCAPD 2024)
Breckenridge, Colorado, USA. July 14-18, 2024
Peer Reviewed Conference Proceeding

Designing Process Systems for Net-Zero Emissions and Nature- and People-Positive Decisions

Bhavik R. Bakshi[a,b,c]*

[a] School for Engineering of Matter, Transport and Energy
[b] School of Sustainability
[c] School of Complex Adaptive Systems, Arizona State University, Tempe, AZ 85281, USA
* Corresponding Author: bhavik.bakshi@asu.edu

ABSTRACT

Sustainability of the chemical and materials industry (CMI) requires it to achieve net-zero emissions of greenhouse gases and other resources while making decisions that have a net-positive impact on nature and society. Many corporations, nations, and universities have pledged to meet such goals but systematic models, methods, and tools to guide this transition are missing. We present a framework to meet this need. It involves developing a comprehensive, open access model of the global CMI. In addition to existing technologies, this model includes emerging alternatives for renewable energy, circularization, and carbon capture, utilization and storage. Systematic methods help identify innovation opportunities and develop roadmaps that account for long-term changes such as technology evolution and climate change. Meeting the goal of net-zero emissions requires inclusion of life cycle impacts. Nature-positive decisions need to encourage ecological protection and restoration. This is enabled by a multiscale framework for determining the absolute environmental sustainability of products and processes by accounting for the availability of ecosystem services and their carrying capacities at multiple spatial scales. People-positive decisions need to account for the benefits to society versus harm. Issues of social justice and equity also need to be included in the decisions. More work has focused on the goal of net-zero greenhouse gas emissions but the need for better models, methods and applications remains. Nature- and people-positive decisions need to consider spatial and temporal variation of ecological and social systems. Meeting these challenges presents many novel opportunities for socially-relevant process systems engineering.

Keywords: Environment, Life Cycle Analysis, Process Design, Process Synthesis, Interdisciplinary, Net-zero, Ecosystem services, Social equity

MOTIVATION

The last few decades have witnessed a growing interest and urgency in incorporating sustainability in all aspects of human activities including process systems engineering. In process design, early efforts focused on meeting regulations expanded to waste minimization from individual processes and then the entire life cycle. From being a necessary evil, when the environment was included as a constraint in process design, environmental protection is becoming a source of competitive advantage, and is routinely included as an objective along with conventional economic goals. These efforts have resulted in methods for reducing the environmental impact of manufacturing processes [1]. Expanding the system boundary to include the life cycle has helped in reducing the chance of unintended harm due to emissions shifting along the life cycle. However, these efforts are not enough for ensuring sustainability for the following reasons.

- Reducing emissions is necessary but not good enough. This is because for many categories, it is urgent that we reduce emissions to zero or even negative. The most important in this category is GHG emissions, but zero emissions are also needed for water, particularly in arid regions of the world, and eventually for all other emissions and resources as well.

- Environmental sustainability requires all human activities to respect nature's capacity, but most approaches do not include ecosystems and their capacity in system design. These approaches need to not only account for and respect nature's limits but also encourage protection and restoration of ecosystems.
- Chemical processes have substantial positive and negative impacts on society. The positive impact includes improvement in our standard of living, employment opportunities and economic growth, while negative impacts are due to resource use, emissions, and other side effects. The net impacts on society need to be positive while preventing social inequities and injustice.

To address these shortcomings, human activities need to have net-zero emissions and resource use while resulting in nature- and people-positive decisions [2]. The goal of net-zero emissions of greenhouse gases (GHG) is currently the most active area of global effort across disciplines. It is covered by the United Nations Framework Convention on Climate Change and most corporations, university campuses, and nations have pledged to achieve net-zero GHG emissions within a few decades. Nature-positive means that decisions should result in restoration and protection of natural ecosystems and their biodiversity. This will result in the production of ecosystem goods and services, which are essential for sustaining human activities and well-being. Many nations and corporations are pledging to make nature-positive decisions so that biodiversity loss can be stopped and reversed by 2050 [3,4]. People-positive means that any negative impact of human activities should be less than the positive impacts. In addition, the impact should also be socially just, that is, the negative impact should not be a function of factors such as race or class [5]. Studies of the positive economic benefits and negative health impacts and climate change due to air pollution of sectors in the U.S. economy identify sectors with net-negative impact.

These goals are analogous to the triple bottom line [1] but take this farther by accounting for specific goals of the Paris Accord for reducing GHG emissions, respecting nature's capacity, and doing more good than harm to people. Such pledges and efforts toward meeting them are commendable. However, achieving these goals in an economically feasible manner poses a formidable challenge since it will require transformation of industry and its supply chain in a manner and at a scale that is likely to be unprecedented. It will require innovation, and while accounting for diverse stakeholders, may result in compromise or win-win solutions. The need for such transformation is urgent since the impacts of the current approach continues to worsen the effects of climate change, ecological degradation, and societal inequities. As conveyed in a recent emissions gap report, "the international community is falling far short of the Paris goals, with no credible pathway to 1.5°C in place. Only an urgent system-wide transformation can avoid climate disaster" [6].

Process Systems Engineering (PSE) has a unique opportunity to contribute to meeting these challenges since they require a systems view and can benefit from its methods and tools [7]. For industry, campuses, and nations to meet their pledges, they need data, models and methods to evaluate current activities, identify emerging options, and to guide the transition. This paper defines the problem and identifies the challenges in becoming net-zero, nature-positive and people-positive. We present a framework for meeting these goals, summarize current efforts and identify future needs and opportunities.

FRAMEWORK FOR GUIDING THE TRANSITION

A general framework for guiding industry transition to a net-zero, nature-positive and people-positive future is shown in Figure 1. It relies on advanced PSE methods for modeling the current and future chemical and materials industry (CMI) pathways, evaluating trade-offs, guiding innovation and developing roadmaps to meet the specified pledges. More details about each step are provided in the rest of this section.

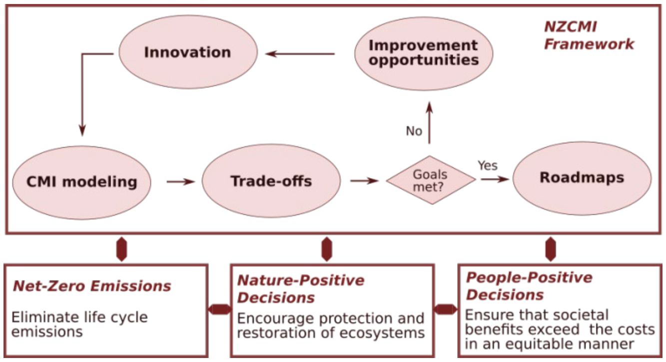

Figure 1. Framework for guiding the transition to net-zero emissions, nature- and people-positive decisions.

Modeling the CMI

Transforming the chemicals and materials industry (CMI) to meet the goals of net-zero, nature-positive and people-positive decisions requires models of the industrial activities and their life cycles. Ideally, such a model should include details about the underlying stoichiometry, reactions, cost, and technologies of current and emerging technologies. Such models have been developed by companies such as S&P Global and used in academic research [8,9]. However, such models do not permit widespread academic research due to their licensing constraints and high cost. A recent model of the CMI [10] overcomes these barriers due to its open access license and no cost for non-commercial use. This model can provide the superstructure of current and emerging technologies relevant to CMI. The matrix representation enables easy linking with life cycle inventory datasets from which the trade-offs between economic, environmental, social, and circularity objectives for different pathways may be identified.

Table 1. Ranking innovations for sustainable circular economy of grocery bags based on improvement potential (UU*) and readiness level (RL) [11].

Rank	Innovation	RL	UU*	Ranking criterion
1	Catalytic pyrolysis of segregated LDPE	7	0.85	0.621
2	Alkaline hydrolysis of PLA to LA using ionic liquids	2	1.83	0.611
3	Linear alkyl benzenes from sorted PE	2	1.83	0.610
4	Bio-polyethylene from sugarcane based bio-ethanol harvested in Brazil	7	0.8	0.603

Guiding Innovation

The desired transition to net-zero, nature-positive and people-positive is unlikely with currently used alternatives. Therefore, innovations in technologies, policies, and behavior are needed. Approaches such as hotspot analysis and sensitivity optimization can be used to determine where to focus future research efforts. Results from applying such an approach to alternatives relevant to develop sustainable and circular grocery bags are shown in Table 1 [11]. Here, the improvement metric, UU* is the distance between utopia points of the Pareto surface with current alternatives and the surface after including the new alternative. The ranking criterion is the geometrics mean of the readiness level and UU*. Finding potential innovations can rely on fundamental knowledge in chemistry databases, trade and patent literature and journals [12]. Artificial Intelligence methods for text mining and large language models can also help [13].

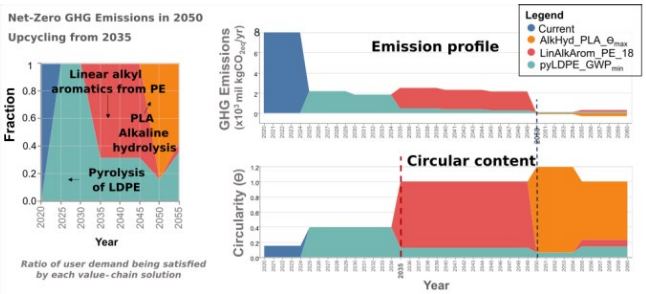

Figure 2. Roadmapping results for transforming grocery bags to net-zero GHG emissions [14].

Roadmapping

Once adequate alternatives are available for meeting a goal such as net-zero emissions, a roadmap needs to be developed to guide the transition. Given the long time horizon of the roadmap, the roadmapping approach should account for changes over this time period in aspects like technology evolution, climate change, improvement in the energy grid and changes in the economy. Such a problem has recently been formulated as a long-term planning problem which can be solved by methods such as robust optimization and multi-period stochastic programming [14]. Typical results from application of this approach to roadmapping for grocery bags with net-zero emissions is shown in Figure 2. This framework models technology evolution as continuous time Markov chains and may be linked with integrated assessment models of climate change and other large-scale changes.

NET-ZERO EMISSIONS

Net-zero emissions are achieved when the direct and indirect emissions over the entire life cycle are zero. Some definitions consider a 90% reduction to be adequate for making claims of "net-zero". Accounting for net-zero emissions relies on the approach of life cycle assessment and life cycle inventory databases. However, unlike the broad focus on diverse resources and impacts in LCA, most current efforts toward net-zero emissions focus only on GHG emissions. For industry to reach net-zero emissions, available alternatives belong to three broad categories: input-side technologies such as use of renewable sources of energy, circularity technologies such as mechanical and chemical recycling, and output side technologies such as carbon capture, utilization and storage (CCUS). For the hard-to-decarbonize CMI sector, circularity technologies are of critical importance since along with reducing GHG emissions, they can simultaneously reduce consumption of resources and pollution due to plastics. Reliance on CCUS may be essential for meeting goals of the Paris Accord. Reliance on renewable resources is also critical, but such technologies are much more materials intensive than nonrenewable technologies. This may result in larger land use change and biodiversity loss due to agriculture, mining, and other land-intensive activities. Land use change can also contribute to achieving net-zero emissions by the implementation of nature-based solutions such as reforestation. For such solutions, it may be best to avoid tree plantations but rely on restoring native vegetation and biodiversity. This is likely to simultaneously contribute to all three goals of net-zero, nature-positive and people-positive solutions.

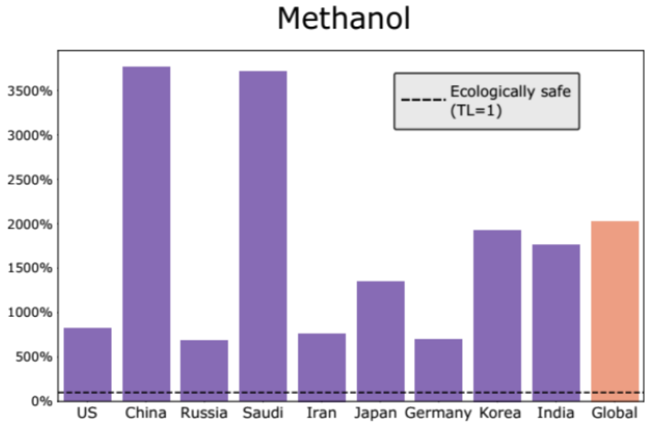

Figure 3. Transgression of the ecological boundary for climate change for methanol in selected nations [17]. Orange bar shows the transgression determined by direct downscaling without considering geographical variation in nature's capacity [16].

NATURE-POSITIVE DECISIONS

To determine whether decisions are nature-positive requires knowing the ecological impact of an activity and ensuring that ecological protection and restoration exceeds this impact. Such decisions can benefit from knowledge about the goods and services provided by nature, since that can help quantify ecological impact and restoration. A popular approach related to nature-positive decisions is based on the concept of planetary boundaries [15], which identifies the "safe operating space" for humanity. This space is based on ensuring that human activities do not exceed global ecological limits for impacts like climate change, biodiversity loss, water scarcity etc. This approach has been used to define metrics for absolute environmental sustainability, and such metrics have been calculated for various processes and products [16,17]. The result is insight into the extent to which a specific human activity transgresses planetary boundaries. Most such approaches rely on normative methods to downscale global planetary boundaries to local scales in proportion to quantities such as economic value addition, emissions, population, etc. Unfortunately, approaches based on direct downscalling of planetary boundaries [16] need not encourage ecosystem restoration and protection because such an approach can "give away" ecosystem capacity from privately owned land to others due to their larger contribution in terms of the selected downscaling approach [17]. This approach utilizes ecological data and models to determine ecological boundaries at multiple spatial scales can provide insight into the degree of transgression of ecological boundaries and encourage.

PEOPLE-POSITIVE DECISIONS

For a decision to be people-positive, its benefits to society should outweigh any harm. Such quantification may be done by representing the benefits and harm in monetary units. The benefits may be indicated by the economic value added by the activity while the harm can be quantified by the monetary value of lost time due to illness, disability or death. Such a study of the US economy found that for sectors such as fossil-based electricity generation, sewage treatment, and stone quarrying, the negative impact from air pollution and climate change are larger than the economic value addition from these sectors [18]. Using the framework of techno-ecological synergy for designing integrated networks of industrial and ecological systems can convert a net-negative manufacturing process into a net-positive TES system. This is by planting native and biodiverse trees in the vicinity of the manufacturing process to reduce the impact of air pollution while also obtaining other ecosystem services [19].

Another aspect of people-positive decisions involves accounting for social justice and equity. This involves at least two aspects: Industry has contributed to social inequity due to the establishment of regions where the negative impacts of industrial activity are borne disproportionately by disadvantaged communities resulting in the formation of regions such as "cancer alleys" [20]. Secondly, a minimum consumption of resources and emission of pollutants is necessary to ensure that the basic needs of a community or region are met. Thus, for decisions to be ecologically safe and socially just, they need to respect ecological limits while meeting basic needs. This operating space is referred to as the "safe and just space" (SJS) for humanity. People-positive engineering decisions require quantification of the SJS and its inclusion in process engineering methods. A recent step in this direction considers specific ecosystem services and determines the safe space or "ecological ceiling" using the TES framework described in the previous subsection. The just threshold or "social foundation" is determined as a function of the minimum food-energy-water consumption of the population in a selected region that is needed for their well-being, and the technologies used for meeting their needs. Based on this information, the SJS has been determined for various nations in terms of the ecosystem services of carbon sequestration and water provisioning [21]. Such results are being incorporated in process and supply chain design problems and will be included in the revised version of this manuscript.

CONCLUSIONS

Rather than just reducing emissions and environmental impact, designs for sustainability need to also meet goals of net-zero emissions particularly for greenhouse gases, respect nature's capacity while protecting and restoring ecosystems, and contribute to societal well-being and equity. Many corporations, universities and nations have pledged to meet such goals. This work describes a framework to guide industry transformation toward meeting these goals of net-zero emissions, and nature- and people-positive designs and decisions. A basic requirement for such work is the availability of a comprehensive superstructure model of the chemicals and materials industry that incudes current and emerging technologies. The effect of business strategies and economic policies should also be included in such models. Developing the roadmap to meet corporate goals requires advanced optimization methods and approaches for dealing with uncertainties. Discovering innovations may be enabled by mining chemistry and engineering databases. Quantifying the metrics of net-zero emissions relies on life cycle assessment. Metrics for nature-positive decisions can use ecological models and data at multiple spatial scales, while those of people-positive decisions need to consider demographics and social equity. Meeting these goals is an urgent need that requires engineering to go beyond its traditional narrow, technocentric boundary. Companies that are successful at navigating these challenges are more likely to grow and prosper while addressing economic, environmental and social needs.

ACKNOWLEDGEMENTS

Partial funding was provided by the National Science Foundation, The Global Kaiteki Center at Arizona State University and the Gretchen and Michael Mavrovouniotis Philanthropic Fund.

REFERENCES

1. Bakshi, B. R. Toward Sustainable Chemical Engineering: The Role of Process Systems Engineering. Annual Review of Chemical and Biomolecular Engineering 10:265-288, (2019)
2. Schlosser, P., Rockström, J., Edwards, C., Mirazo, P., Heilemann, A., Kitzmann, N. H., Krobjinski, S. L. Accelerating transformations for a just, sustainable future: 10 'Must Haves'. Global Sustainability 6 (2023)
3. Locke, H., Rockström, J., Bakker, P., Bapna, M., Gough, M., Hilty, J., Lambertini, M., Morris, J., Polman, P., Rodriguez, C. M. et. al. A nature-positive world: the global goal for nature. Global Goal for Nature Group, (2021)
4. zu Ermgassen, S. O., Howard, M., Bennun, L., Addison, P. F., Bull, J. W., Loveridge, R., Pollard, E., Starkey, M. Are corporate biodiversity commitments consistent with delivering 'nature-positive' outcomes? A review of 'nature-positive' definitions, company progress and challenges. Journal of Cleaner Production 379:134798 (2022)
5. Obura, D. O., DeClerck, F., Verburg, P. H., Gupta, J., Abrams, J. F., Bai, X., Bunn, S., Ebi, K. L., Gifford, L., Gordon, C. et. al. Achieving a nature- and people-positive future. One Earth, 6:105-117 (2023)
6. United Nations Environment Program. Emissions Gap Report. https://www.unep.org/resources/emissions-gap-report-2022 (2022)
7. Stephanopoulos, G., Bakshi, B. R., Basile, G. Reinventing the Chemicals/Materials Company: Transitioning to a Sustainable Circular Enterprise. In Yamashita, Y., Kano, M. (Eds.) 14th International Symposium on Process Systems Engineering, 49:67-72 (2022)
8. DeRosa, S. E., Kimura, Y., Stadtherr, M. A., McGaughey, G., McDonald-Buller, E., & Allen, D. T. Network modeling of the US petrochemical industry under raw material and Hurricane Harvey disruptions. Industrial & Engineering Chemistry Research, 58(28), 12801-12815 (2019).
9. Meys, R., Kätelhön, A., Bachmann, M., Winter, B., Zibunas, C., Suh, S., Bardow, A. Achieving net-zero greenhouse gas emission plastics by a circular carbon economy. Science 374:71-76 (2021)
10. Sen, A.; Stephanopoulos, G. & Bakshi, B. R. Mapping Anthropogenic Carbon Mobilization through Chemical Process and Manufacturing Industries. In Yamashita, Y. & Kano, M. (Eds.) 14th International Symposium on Process Systems Engineering, 49:553-558 (2022)
11. Thakker, V., Bakshi, B. R. Ranking Eco-innovations to Enable a Sustainable Circular Economy with Net-Zero Emissions. ACS Sustainable Chemistry and Engineering 11:1363-1374 (2023)
12. Coley, C. W., Green, W. H., Jensen, K. F. Machine learning in computer-aided synthesis planning. Accounts of chemical research 51:1281-1289 (2018)
13. Kumar, A., Bakshi, B., Ramteke, M., Kodamana, H. Recycle-BERT: Extracting Knowledge about Plastic

Waste Recycling by Natural Language Processing, ACS Sustainable Chemistry and Engineering, 11, 12123-12134 (2023)

14. Thakker, V., Bhavik Bakshi. Mapping the Path to a Net-Zero Chemicals Industry by Long-Term Planning with Changes in Technologies and Climate. Authorea Preprints (2023)
15. Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., 3rd, Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., et al. A safe operating space for humanity. Nature 461:472–475 (2009)
16. Bachmann, M., Zibunas, C., Hartmann, J., Tulus, V., Suh, S., Guillen-Gos albez, G., Bardow, A. Towards circular plastics within planetary boundaries. Nature Sustainability, 6(5):599–610 (2023)
17. Xue, Y., Bakshi, B. R., Need science-based metrics to guide plastics within planetary boundaries, Nature Sustainability, submitted (2023)
18. Muller, N. Z., Mendelsohn, R., Nordhaus, W. Environmental Accounting for Pollution in the United States Economy. American Economic Review 101:1649-1675 (2011)
19. Shah, U., Bakshi, B. R. Toward Nature-Positive Manufacturing by Adapting Industrial Processes to Pollution Uptake by Vegetation. ACS Sustainable Chemistry and Engineering, 9:16709-16718 (2021)
20. Singer, Merrill. "Down cancer alley: the lived experience of health and environmental suffering in Louisiana's chemical corridor." Medical Anthropology Quarterly 25.2 (2011): 141-163.
21. Aleissa, Y. M., Bakshi, B. R. Possible but Rare: Safe and Just Satisfaction of National Human Needs in Terms of Ecosystem Services. One Earth 6:409-418 (2023)
