Engineering-level input-output modeling for low-carbon infrastructure planning

Sangwon Suh
Bren School of Environmental Science and Management
University of California
Santa Barbara, CA 93106-5131
Phone: (805) 893-7185 | email: suh@bren.ucsb.edu

Abstract

Avoiding the most dangerous consequences of climate change requires balancing anthropogenic greenhouse (GHG) emissions with natural sinks by the second half of this century. To do so, the global economy is expected to need 50-100 trillion USD infrastructure investments for low-carbon transition over the next a few decades. The types of infrastructure needed include energy (generation, transmission, and storage infrastructure), transportation (public transportation, road, and charging infrastructure), built environment (commercial and residential building infrastructure), and industrial production (manufacturing infrastructure). The effort to measure the environmental implications of low carbon infrastructure development often benefit from the information at multiple resolutions including sectoral and engineering levels. Discussed here are a number of recent examples where engineering-level data are used in an input-output framework to quantify carbon mitigation potential. First, the Green Technology Choice project by the international resource panel (IRP) examines over 60 low-carbon technologies in terms of their life-cycle GHG mitigation potential by integrating engineering- and sector-level input-output data with environmental extensions. The results show that both low-carbon energy supply and energy demand management technologies are needed for substantial GHG reductions. Second, The Weight of Cities project by IRP analyzes the impacts of deploying low-carbon infrastructure for bus rapid transit, district heating, green commercial building, and strategic densification of urban systems applied to over 84 global cities. The results show that GHG footprint of these cities would increase by 58%–116% by 2050. Low-carbon infrastructure and strategic densification, however, have the potential to curve down GHG emissions to 17% below the 2010 level in 2050. Finally, a series of articles by Kätelhön and colleagues examine chemical production processes and their GHG mitigation potentials using technology choice model, which is an engineering-level rectangular input-output model. These papers show that engineering data can be integrated into rectangular input-output structures for technology-choice questions. Toward the end of the presentation, I will discuss the benefits as well as the challenges in using engineering level data, and the synergies between the input-output and engineering communities working in the field of low-carbon transition.

Keywords: input-output analysis, engineering-level data, rectangular choice of technology model, technology choice model, low carbon infrastructure, greenhouse gas emissions, climate change

1. Introduction

Climate change mitigation is recognized as a global imperative by the international community.[1] Reducing global greenhouse gas (GHG) emissions to avoid the dangerous consequences of climate change requires a large-scale infrastructure reform in energy, building, and transportation sectors[2]. Estimates indicate that up to 100 trillion USD investment would be needed for the next a few decades to meet the infrastructural needs, part of which is devoted to low-carbon transition[2–4]. Main areas need to be addressed include energy (generation, transmission, and storage infrastructure), transportation (public transportation, road, and charging infrastructure), built environment (commercial and residential building infrastructure), and industrial production (manufacturing infrastructure).[5]

Understanding the environmental implications of such infrastructure investments requires a holistic understanding of the economy and the technologies involved for which life cycle assessment (LCA), material flow analysis, input-output analysis, and their combinations have been utilized[6–11]. Input-output analysis (IOA) and related models and tools such as the Rectangular Choice of Technology (RCOT) model provide a good starting point for analyzing the environmental implications of infrastructure development, while the default sectoral resolution of input-output table often falls short in providing necessary details and complexities in infrastructure technologies. Combining engineering-level information with input-output data and modeling frameworks, however, proved to overcome some of the limitations in both engineering-level and sectoral models. In this paper, we will review some of the recent papers that use engineering-level details under an input-output framework to address the environmental implications of infrastructure development.

The objective of the paper is to provide an overview of the approaches and recent applications to environmental assessment of infrastructure development where engineering-level data are utilized under an input-output framework. In particular, this paper focuses on the following examples.

- **Low-carbon infrastructure systems**: Suh, S., Bergesen, J., Gibon, T. J., Hertwich, E. & Taptich, M. Green Technology Choices: The Environmental and Resource Implications of Low-Carbon Technologies. *U. N. Environ. Programme Nairobi Kenya* (2017).
- **Urban infrastructure systems**: Bergesen, J. D., Suh, S., Baynes, T. M. & Musango, J. K. Environmental and natural resource implications of sustainable urban infrastructure systems. *Environ. Res. Lett.* **12**, 125009 (2017).
- **Industrial infrastructure systems**: Kätelhön, A., Meys, R., Deutz, S., Suh, S., Bardow, A. The Climate Change Mitigation Potential of Carbon Capture and Utilization in the Chemical Industry. *Proc. Natl. Acad. Sci. Forthcoming*.
- **Building infrastructure systems**: Building for Environmental and Economic Sustainability (BEES) and Building Industry Reporting and Design for Sustainability (BIRDS) databases.[12–14]

2. Low-carbon infrastructure system

In this example, over technical specifications of over 60 different low-carbon technologies that either generate low-carbon electricity or reduce energy consumption are evaluated at regionalized global scale using process- and input-output LCA techniques[15]. The technical specifications of these technologies are translated to inputs and outputs per unit of functional flow (useful product or service such as 1 kWh of renewable electricity), which are used to construct direct requirement vector for each technology. These vectors are collated and connected to background processes and multi-regional input-output tables through a hybrid LCA approach[16,17].

The results show that both low-carbon infrastructure on electricity generation and efficiency technologies are needed to achieve a deep cut in GHG emissions by 2050 (Fig. 1).

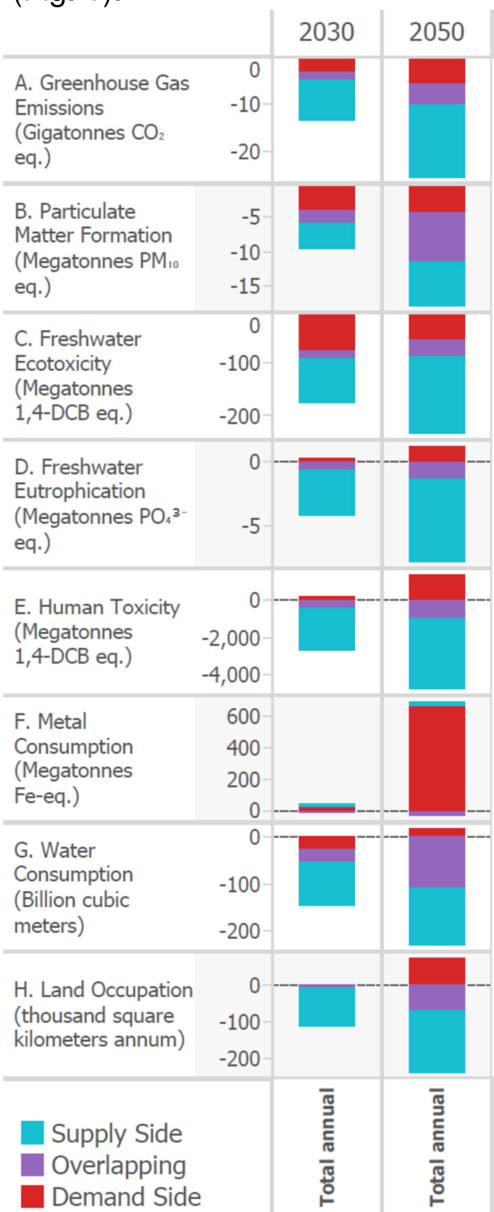

Figure 1. Combined change in life cycle environmental impacts as a result of deploying low-carbon supply-side and demand side technologies under the 2 degree Celsius scenario.[8]

Furthermore, the low-carbon technologies examined provided not only greenhouse gas (GHG) emissions reduction benefits but also various co-benefits including reductions in human toxic impacts, ecosystem health impacts, water consumption, land use, acidifying substance emissions, and ozone layer depleting substance emissions.[7,8,18] The only exception was metal resources consumption, which showed an increase in life cycle impacts (Fig. 2)

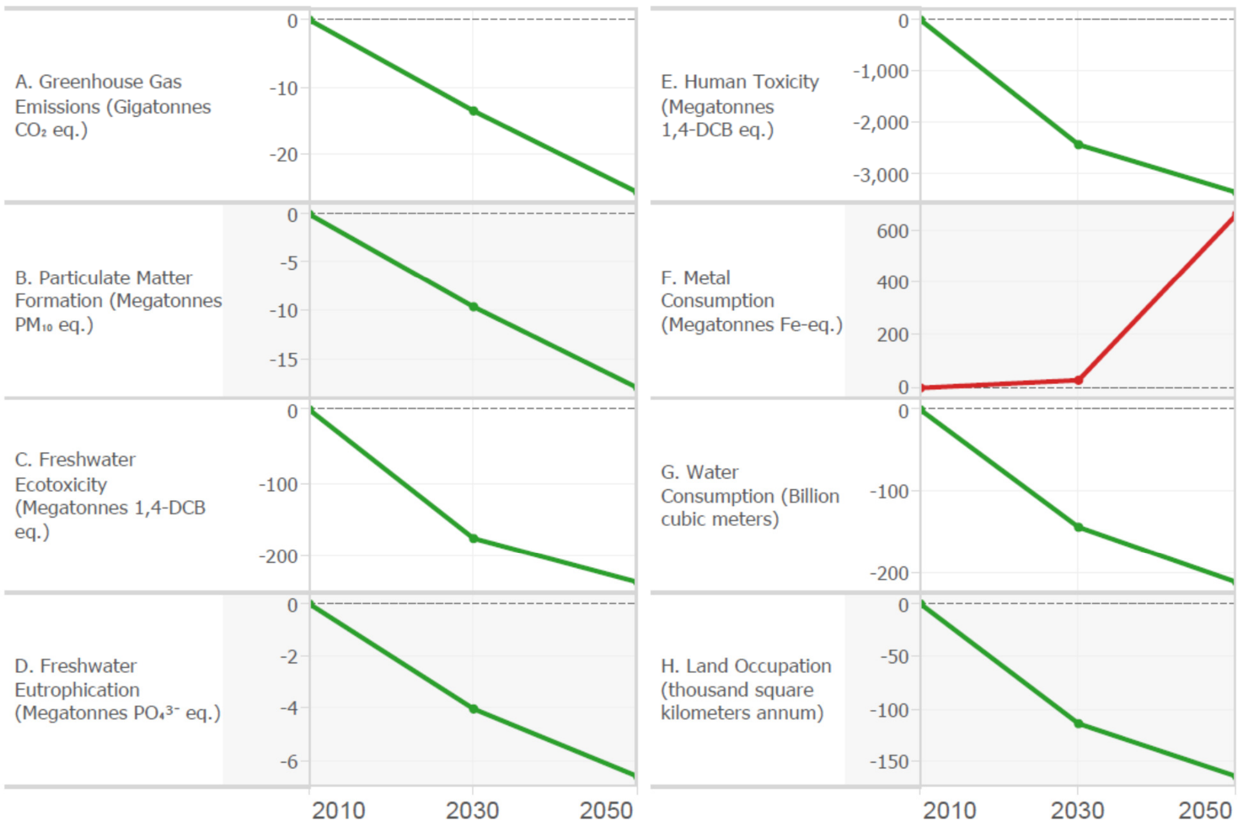

Figure 2. Changes in life cycle environmental impacts as a result of deploying low-carbon demand-side technologies under 2 degree Celsius scenario. [8]

3. Urban infrastructure systems

In this example, the potential life cycle environmental benefits of deploying resource-efficient urban infrastructure systems including (1) Bus Rapid Transit (BRT), (2) energy efficient buildings, (3) district energy systems, and (4) strategic densification were evaluated. Given that climatic, socio-economic, and technological conditions differ widely among the global cities, data were collected at each city-level for a total of 84 global cities, and were integrated with engineering-level datasets on each technology. The results show that GHG footprint of these cities would increase by 58%–116% by 2050 in the course of urbanization. Low-carbon infrastructure and strategic densification, however, have the potential to curve down GHG emissions to 17% below the 2010 level in 2050 (Fig 3).

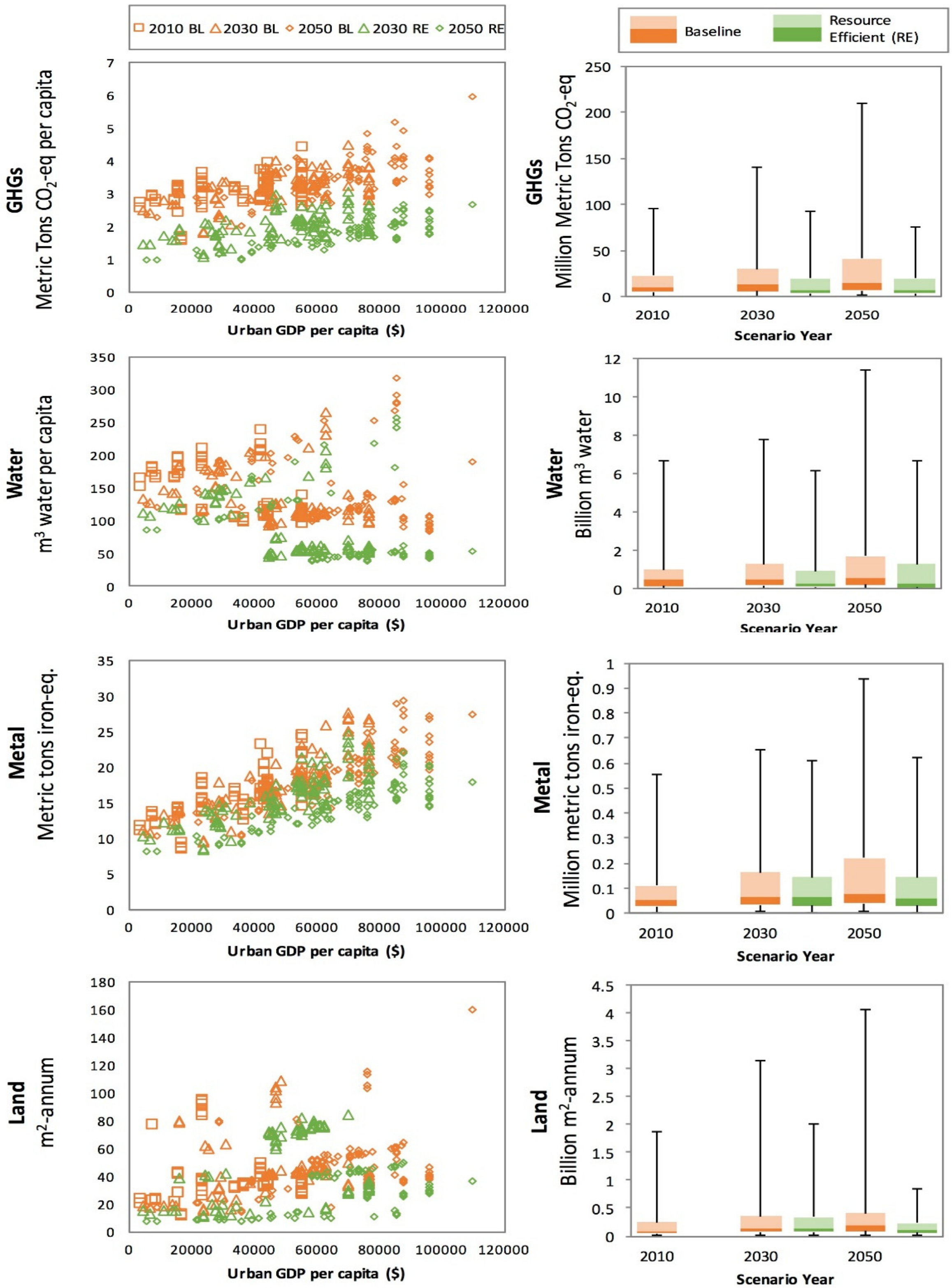

Figure 3. City-by-city life-cycle impacts under the current and resource-efficient urban infrastructure systems[9]

4. Manufacturing infrastructure systems

In this example, engineering-level inputs and outputs data on chemical production and carbon capture and utilization processes were collected, structured into a Technology Choice Model (TCM) format, which resembles the Rectangular Choice of Technology (RCOT) model in input-output tradition, and lowest GHG emission pathways were analyzed. The manuscript is currently under an embargo and the results cannot be reproduced here. However, by the time of presentation, the embargo will be released.

5. Building infrastructure systems

The BEES and BIRDS databases provide the economic, energy, and environmental profiles of building materials and structures.[12–14] The underlying dataset is based on hybrid unit and hybrid resolution supply and use matrices (Fig. 4). The framework provides an opportunity to utilize the most detailed technological information while keeping the system boundary as broad as possible. The resulting databases are accessible online through the NIST website.

	Detailed product	Item-level product	Standard product	Unit process	Item-level industry	Standard industry	Final demand	Total
Detailed product				Detailed product use by unit process	(Detailed product use by item-level industry)	(Detailed product use by standard industry)		
Item-level product				Cut-offs linked to item-level product	Item use by item-level industry	Item use by standard industry	Final demand on items	
Standard product				Cut-offs linked to standard products	Standard product use by item-level industry	Standard product use by standard industry	Final demand on standard products	
Unit process	Supply by unit process							
Item-level industry		Supply by item-level industry						Total output by item industry
Standard industry			Supply by Standard industry					Total output by standard industry
Value added		Value added	Value added					Total value added
Total	Total supply of detailed products	Total supply of items	Total supply of standard products					

Figure 4. The basic supply-use structure of hybrid BEES database[13]

6. Conclusions and discussion

Input-output analysis and associated modeling frameworks provide useful basis for analyzing the life cycle environmental impacts of infrastructure systems. The framework also allows the use of physical-unit data at engineering-level resolution. In this paper, we discussed a few examples where engineering-level data are integrated into input-output framework and data for understanding the environmental implications of infrastructure developments.

Future research can further integrate the economic dimensions of infrastructure developments as well as stochastic, non-linear and dynamic problems such as stochasticity in intermittency of renewables, and nonlinear responses in capacity factors of renewables to battery capacity development.

References

1. UNFCCC. *Adoption of the Paris Agreement*. (2015).
2. New Climate Economy. *The sustainable infrastructure imperative: financing for better growth and development*. (2016).
3. New Climate Economy. *Better growth, better climate*. (2014).
4. Oxford Economics. *Global Infrastructure Outlook*. (2017).
5. Swilling, M., et al. *The Weight of Cities*. (2018).
6. Bergesen, J. D., Tähkämö, L., Gibon, T. & Suh, S. Potential Long-Term Global Environmental Implications of Efficient Light-Source Technologies. *J. Ind. Ecol.* **20**, 263–275 (2016).
7. E. Hertwich *et al. Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production*. (UNEP-International Resource Panel, 2015).
8. Suh, S., Bergesen, J., Gibon, T. J., Hertwich, E. & Taptich, M. Green Technology Choices: The Environmental and Resource Implications of Low-Carbon Technologies. *U. N. Environ. Programme Nairobi Kenya* (2017).

9. Bergesen, J. D., Suh, S., Baynes, T. M. & Musango, J. K. Environmental and natural resource implications of sustainable urban infrastructure systems. *Environ. Res. Lett.* **12**, 125009 (2017).

10. Kätelhön, A., Bardow, A. & Suh, S. Stochastic Technology Choice Model for Consequential Life Cycle Assessment. *Environ. Sci. Technol.* **in press**, (2016).

11. Kätelhön, A., von der Assen, N., Suh, S., Jung, J. & Bardow, A. Industry-Cost-Curve Approach for Modeling the Environmental Impact of Introducing New Technologies in Life Cycle Assessment. *Environ. Sci. Technol.* **49**, 7543–7551 (2015).

12. Lippiatt, B. C., Greig, A. L. & Lavappa, P. D. *BEES Online: Life Cycle Analysis for Building Products*. (National Institute of Standard and Technology (NIST), 2010).

13. Suh, S. & Lippiatt, B. C. Framework for hybrid life cycle inventory databases: a case study on the Building for Environmental and Economic Sustainability (BEES) database. *Int. J. Life Cycle Assess.* **17**, 604–612 (2012).

14. Lippiatt, B. C., Kneifel, J. D., Lavappa, P. D., Suh, S. & Greig, A. L. *Building Industry Reporting and Design for Sustainability (BIRDS) Technical Manual and User Guide*. (2013).

15. Suh, S. *et al.* System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environ. Sci. Technol.* **38**, 657–664 (2004).

16. Suh, S. Functions, commodities and environmental impacts in an ecological–economic model. *Ecol. Econ.* **48**, 451–467 (2004).

17. Gibon, T. *et al.* A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change. *Environ. Sci. Technol.* (2015). doi:10.1021/acs.est.5b01558

18. Hertwich, E. G. *et al.* Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proc. Natl. Acad. Sci.* 201312753 (2014). doi:10.1073/pnas.1312753111