Sustainability of PV System
Duration: 9/1/2014 – 8/30/2017
Total: ~$250,000
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OBJECTIVES

Researchers from Michigan State University will continue working with all other researchers on the SEP team while leading the research component of Thrust 2 (Sustainability Assessment of the New PV Technology and Production). Funds are requested to support two doctoral students at the Department of Geography. The ***objective*** is to explore the sustainability of the materials, cell components, and manufacturing processes proposed and studied in **Thrust 1** through LCSA of the environmental, economic, and sociopolitical measures of alternative PV options. We ***hypothesize*** that trade-offs among the options of sustainability aspects may be off-balance or appear to compete over short timelines but may positively correlate over long time scales. The sustainability assessment will provide a metric of index, which can provide important feedback for **Thrust 1**. Two specific tasks are:

Task 1: Development of dynamic scenarios

To assess the sustainability of PV technology, we will model alternative future states, suggesting that multiple scenarios need to be developed to represent possible and consistent alternatives to the proposed PV technology system. In our approach, we treat scenario development as a major research task (vs. a set of pre-defined scenarios) that will be reiteratively modified based on the LCSA output (Task 2).

Task 2. Integrated assessment models via SEM

The database developed above is intricate. Among the promising methods that have been applied toward this kind of complex system are neural networks, path analysis, regression trees, SEM, and traditional multivariate analysis.[124,125] For this task, multiple variants of the SEM will be used to assess the vulnerability and uncertainties of different options. As a framework for developing and evaluating complex hypotheses about systems, the SEM uses two or more structural equations to model multivariate causal relationships. Causal models involving either manifest variables, latent variables, or both are typically developed based on theoretical knowledge and designed to represent competing hypotheses about the processes responsible for data structure.

Another major challenge for modeling the complexity of our systems is the uncertainty due to data quality, measuring errors, or other unpredictable underlying mechanisms. The Bayesian analysis has been widely used for this. The Bayesian analysis regards parameters as random variables drawn from prior distributions that represent our previous knowledge about that variable. Parameters are then estimated as a combination of likelihood, their prior distributions, and their posterior distribution (i.e., uncertainty analysis). All statistical inferences (point and interval estimates, hypothesis tests) then follow from posterior summaries. When exact analytical solutions are not possible, common in complex analyses, the Bayesian analysis estimates parameter values (and latent variables) from the posterior distribution using the Monte Carlo Markov Chain (MCMC) approach, generating close approximations to the real parameters. This analytical framework provides great flexibility in the estimation of the parameters and allows the analysis of fairly complex problems, as in our case. Vulnerability Analysis will be performed under alternative scenarios. We will convene in our first year to develop different options for EES. Model trials will be used to train us in revising the scenarios.

MAJOR RESULTS

We compared life cycle environmental impacts from alternative PV - CdTe (cadmium telluride), CIGS (copper indium gallium diselenide), Zn3P2 (zinc phosphide), and CZTS (copper zinc tin sulfide). A cradle to gate life cycle assessment was conducted to understand the environmental impacts from these technologies. The impacts from Zn3P2 and CdTe were similar and lower than the impacts from CZTS and CIGS. While CdTe has the toxic Cd element, the ecotoxicity impact from material acquisition and processing was higher for Zn and P than for CdTe. In CIGS, the ecotoxicity impact came mainly from Ga and would be significantly reduced if CZTS were to replace CIGS in the commercial market. For all four thin films studied, the contribution of raw materials to total impact was much lower than the impact coming from electricity consumption during the manufacturing stage. Therefore, to reduce environmental impact, future PV technology development should focus more on the process improvement. The manufacturing stages that contributed most to the impact were the absorber layer for CIGS and CZTS and the substrate cleaning for CdTe and Zn3P2. We have extended the assessment of single PV cells/modules to investigate its broader social impacts while considering the technology from the whole building perspective. We studied how the PV technology – as a novel green building technology – might interfere with the building user's pro-environmental attitudes and behaviors.

The Institute for the Built Environment at Colorado State University lists the first and foremost important aspect of a green building as "buildings that teach". To empirically investigate whether and how a green building affords effective communication of sustainability to its users, we used a campus Leadership in Energy and Environmental Design (LEED)-certified building to survey the building users on their perceptions about green designs implemented in the building at different spatial scales (Wu et al. 2017b). The results suggested that users' perceptions about green designs are experienced at different spatial scales. When one prefers a design at the product-scale, such as the educational signs, (s)he tends to neglect the larger space-scale design, such as the tall windows and access to outside views. This finding of dichotomous spatial perspectives of a person might be further manipulated when designing a green building and implementing green designs at multiple spatial scales. For example, other than considering the technological details, one needs to consider where and how to locate an on-site renewable energy technology such as PV to most effectively communicate sustainability.

To promote the development of Social Life Cycle Assessment (SLCA), we conducted a comprehensive review of recently developed frameworks, methods, and characterization models for impact assessment for future method developers and SLCA practitioners (Wu et al., 2014).

We also argue that social life cycle impact assessments (SLCIA) need to incorporate either a type I or type II characterization model. We improved both models by introducing explicit causality by using statistic modeling through development of (1) a quantitative approach to simultaneously identify impact pathways of type II models with multiple impact categories, targeting SLCIA method developers, and (2) a new hybrid model to establish causality between inventory indicators and subcategories, targeting social life cycle assessment practitioners. Methods Causality establishments for type II impact pathways and the new hybrid model are the core requirements for this study. We used structural equation modeling (SEM) to identify the impact pathways for type II characterization models, therefore resolving the issues of unobservability and unvalidatibility in type II models. Using country-level data from the World Bank, the method was applied to an example (Fig. 1). This study was the first attempt in using statistic causal models to quantitatively identify unobservable impact pathways of the type II model and to develop a hybrid model for SLCIA. A SEM that incorporates temporal precedence enables identification of impact pathways with multiple unobservable impact categories. The hybrid model using Bayesian networks represents the subcategories in posterior probabilities instead of absolute scores, helping companies to better develop instructions for future management practices (Wu, et al., 2015).

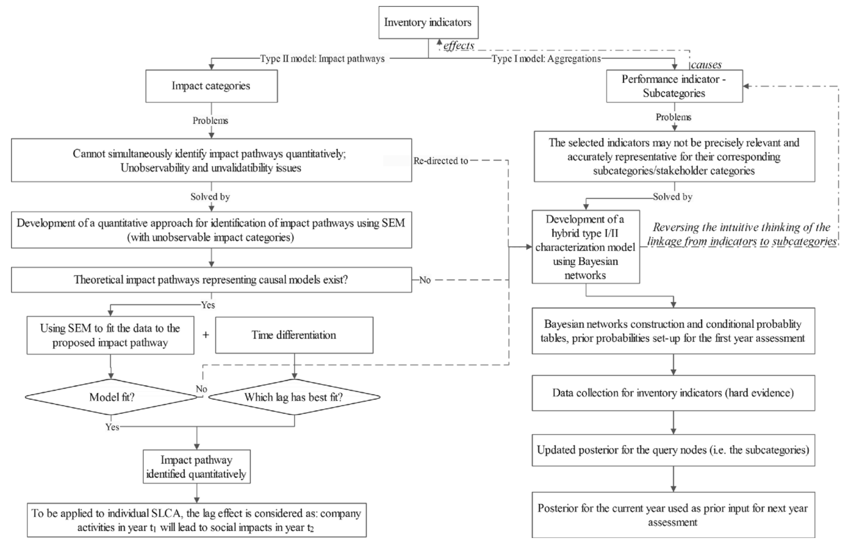


Fig. 1. Two types of SLCIA, their limitations, the proposed approaches for the identification of impact pathways for type II characterization model and the development of a hybrid type I/II characterization model.

Furthermore, we argued that while technology-oriented sustainability assessment frameworks (i.e. focusing and measuring impacts from alternative technologies) are necessary. While human–environment interaction has been studied extensively, it is rarely addressed in the sustainability assessment framework. We have studied human-built environment interaction in the context of green buildings both theoretically (Wu et al. 2017a) and empirically (Wu et al. 2017b). This interaction, combined with the progress addressing the continuous improvement efforts made by an entity, the temporal, spatial, and behavioral dynamics can be simultaneously addressed in a life cycle sustainability assessment using a green building development example (Wu et al. 2017c).

We also attempted to develop a social handprint/footprint (SH/F) reporting framework for the mining industry that can be integrated into product social life cycle assessment (S-LCA). We tested the assessment framework by comparing the social performance of average resource extraction for two major PV technologies in the U.S. – the poly-Si and the CdTe PV. We selected PV because a recent nationwide Gallup poll showed that majority of Americans see solar energy as the top choice among domestic energy sources, with four fifths of respondents saying the U.S. should place more emphasis on solar development than any other energy source. Two existing SLCA frameworks are used as the starting point – the UNEP SLCA guidelines and the PRE handbook. Two important principles adopted from GRI and the PRE handbook are used for constructing the framework: 1) Measure both positive and negative impacts; and 2) Maintain inclusiveness and completeness while focusing on materialistic issues, so that only stakeholders affected by the mining industry are included in the assessment and those social themes/topics that are significant for the evaluation are included. We used the quantitative approach in developing our framework and the impact assessment method. The scale-based approach will also be briefly discussed and demonstrated hypothetically. We used the SH/F framework to compare the social impacts for the material extraction stage of two PV technologies – the poly-Si and the CdTe PV. The comparison would be based on a 1 m^2 final PV module without further normalization to energy production efficiency. The poly-Si technology is most widely deployed – with 90% market share in OECD North America in 2010, followed by CdTe with 9% market share. The framework can further incorporate a temporal scale to observe the changing performance for individual mines, and to acknowledge whether continuous efforts are made collectively toward sustainability at the societal scale. Practically, it can also inform purchasing decisions for downstream companies from the perspective of suppliers' business resilience regarding social sustainability (Fig. 2).

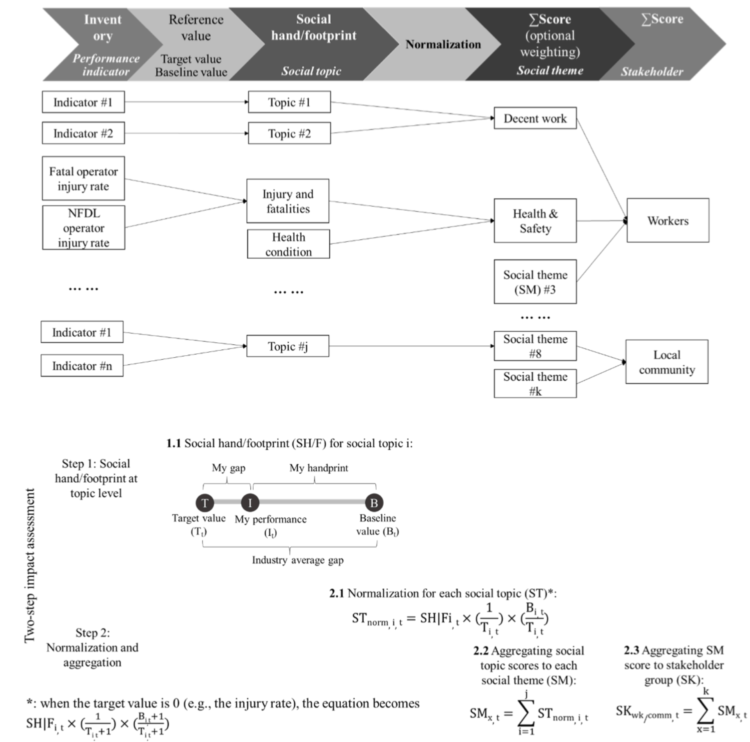


Fig. 2. The structure of our SH/F framework contains following hierarchies: 1) the stakeholder groups, 2) the social themes under each stakeholder group, 3) the social topics under each social theme, and 4) the performance indicator for each social topic (Wu et al., in preparation).

Finally, current sustainability assessment frameworks are technology-oriented – both focusing and measuring impacts from alternative technologies. Nevertheless, technology alone, without consideration of human-object/-environment interaction and behavioral consequences, cannot achieve sustainability. A human dimension must be added and addressed through cultural sustainability. This is especially applicable for the built environment, which reflects the past and shapes the future culture. While human–environment interaction has been studied extensively, it is rarely addressed in the sustainability assessment frameworks. We have studied human-built environment interaction in the context of green buildings both theoretically and empirically. By combining such interactions with the progress addressing the continuous improvement efforts made by an entity, the temporal, spatial, and behavioral dynamics can be simultaneously addressed in a life cycle sustainability assessment using a green building development example (Fig. 3).

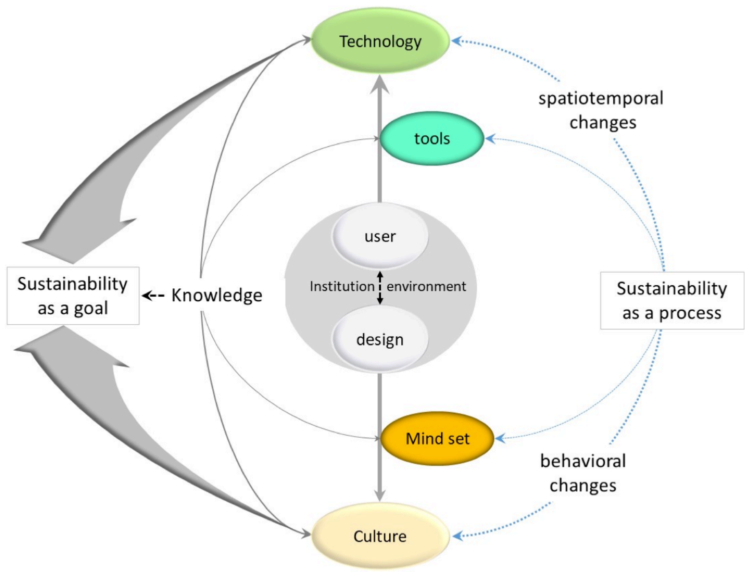


Fig. 3. The role of culture and technology in sustainability development.

OUTCOMES

Thesis

1. Wu, Susie R. 2016. Green buildings and green users: an assessment of using green building environments to communicate sustainability to users. Ph.D., Michigan State University.
2. Fan, A. Simulation of smart electricity grids and markets with agent-based modeling, in progress. Michigan State University.

Journal publications & book chapters

1. Collier, J., S. Wu, and D. Apul. 2014. Life cycle environmental impacts from CZTS and Zn_3P_2 thin film photovoltaic cells. *Energy* 74: 314-321.
2. Wu, R., D. Yang, and J. Chen. 2014. Social life cycle assessment revisited. *Sustainability* 6(7): 4200-4226.
3. Wu, S.R., Chen, J., Apul, D., Fan, P., Yan, Y., Fan, Y. and Zhou, P., 2015. Causality in social life cycle impact assessment (SLCIA). *The International Journal of Life Cycle Assessment*, *20*(9), pp.1312-1323.
4. Fan, Y., Wu, R., Chen, J. and Apul, D., 2015. A Review of Social Life Cycle Assessment Methodologies. In *Social Life Cycle Assessment* (pp. 1-23). Springer Singapore.

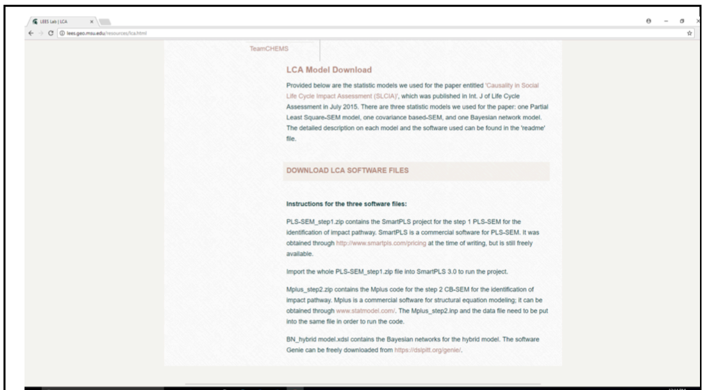
5. Wu, S.R., M. Greaves, J. Chen., and S. Grady. 2017. Green buildings need green occupants: A research framework through the lens of the Theory of Planned Behavior. *Architectural Science Review* 60(1): 5-14.
6. Wu, R., P. Fan, and J. Chen. 2016. Incorporating culture into sustainable development: A cultural sustainability index framework for green buildings. *Sustainable Development* 24(1): 64-76.
7. Fan, Y, J. Chen, G. Shirkey, R. John, R. Wu, H. Park, C. Shao. 2016. Applications of structural equation modeling (SEM) in ecological research: An updated review. *Ecological Processes* 5:19 DOI: 10.1186/s13717-016-0063-3
8. Wu, S.R., X. Li, D. Apul, V. Breeze, Y. Tang, Y. Fan, and J. Chen*. 2017. Agent-based modeling of temporal and spatial dynamics in life cycle sustainability assessment. *Journal of Industrial Ecology* DOI: 10.1111/jiec.12666
9. Wu, S. R, S. K. Kim, H. Park, P. Fan, A. Ligmann-Zielinska, and J. Chen*. 2017. How green buildings communicate green design to the building users? A survey study on a LEED-certified building. *Journal of Green Building* 12(3): 85-100.
10. Fan, Y., Beyza, G., Chen, J., Wu, S.R., Zhou, P., 2016. Pro-environmental behaviors and knowledge: A case study of park visitors in Toledo, Ohio. *Environmental Protection and Ecology* (revision submitted)
11. Wu, S.R., I. Celik, and D. Apul. A social handprint/footprint calculation framework for resource extraction industry: a case study on comparing two major PV technologies in the U.S. *Journal of Clean Productions* (in preparation).
12. Wu, S.R., J. Chen, and others. Human-environment interaction and the behavioral consequences in sustainability. *Nature-Sustainability* (in preparation)

Models & Codes

The original source codes for LCA (Wu SR (2015) Software models for causality in social life cycle impact) is openly posted at: http://lees.geo.msu.edu/resources/lca.html

LCA Training Workshop

To expand our lesson on LCA applications in broadly-defined environmental science, a 2-day training workshop was organized at the LEES Lab during May 12-13, 2017. Nine research assistant at the MSU received the training by Dr. for the lab by Bill Kung of Ecovane Environmental. Nine research assistants received the training, with a software provided by Dr. Kung for 30 days: Susie Wu (Postdoc), Gabriela Shirkey (M.S. student), Fei Lei (Postdoc), Cheyenne Lei (Doctoral student), Maowei Liang (doctoral student), Vincenzo Giannico (visiting doctoral student, Italy), Peiro Sciusco (visiting MS student, Italy), Ranjeet John (postdoc), Hogeun Park (doctoral student). During the workshop, we discussed LCA, eco-design and green supply chain issues, as well as policy



Open access of LCA Modeling codes through the LEES Lab at the Michigan State University and standard development around LCA and applications. We also explored chances for collaboration for the future.

Presentations

1. Fan, Y. Demand for solar electricity from the BRICS countries in the future. American Geography Union Fall Meeting, San Francisco, 2015.
2. Wu, S.R., M. Green, J. Chen, A. Yang, and Y. Tang. Green building design and visual persuasion on occupants' pro-environmental behaviors. In proceedings of the 49th International conference of the Architectural Science Association, , Melbourne, pp. 133-142, December 2-4, 2015.
3. Chen, J. Harmonizing people and nature. Invited Seminar Series, Huadong Normal University, August 2, 2015
4. Chen, J. Harmonizing nature and people. Hanover Seminar Series (invited), Dept. of Forestry, MSU. March 17, 2015.
5. Chen, J. Renewed Challenges: People vs Environment. Wenzhou University, November 4, 2016