Heating system adoption and environmental impact: Insights from coupling an agent-based building-energy model with dynamic LCI data

Theme and subtheme

6. Theory, methods and practice of ecological economics
6.3 Indicators and modelling approaches

Summary

Energy demand from buildings not only accounts for a significant amount of the final energy use and offers massive savings in terms of environmental impacts, but also restricts the speed of change through the long lifetime of our build environment. In this study, an agent-based building-energy model portrays building stock's energy demand and heating systems adoption patterns for a region. The key behavioural elements modelled are homeowners' heating system adoption decision, reflecting the complex interactions between policy interventions, technical and social structure, and individual behaviour. Environmental impacts of the heat demand are then assessed with a dynamic life cycle assessment approach, where the output of the agent-based model is combined with life-cycle inventory data changing over time. The main goal of this study is to shed light on what policy instruments could be most effective in reducing environmental impacts caused by energy demand from buildings.

Extended abstract

Energy demand from buildings and activities in buildings account for 34% of global final energy demand, of which three-quarters are for thermal purposes (GEA, 2012). State-of-the-art technologies as well as non-technological options present a major opportunity to reduce buildings' energy demand drastically in the next couple of decades. According to the Global Energy Assessment Report, energy demand for heating and cooling could be reduced by about 46% by 2050 compared to the 2005 levels by applying today's best practices while still more than doubling the usable floor area. The long lifetimes of buildings and building technologies require immediate action to reduce energy demand, but also present a significant risk of lock-in. If less than state-of-the-art technologies are promoted, global energy demand from buildings will increase by up to 33% (GEA, 2012).

End-use technologies such as heating systems hold the largest potential for climate mitigation (Grubler et al., 2012; Wilson et al., 2012), but there are challenges in terms of sufficient research and development, widespread adoption, as well as appropriate maintenance and usage of these technologies. The total energy demand of buildings is determined by demand levels, the efficiency of the conversion technologies, and the efficiency of supply and distribution networks (Knoeri et al., forthcoming). All of these require more or less active involvement of supply network actors, home owners, and occupiers; offer a variety of efficiency options over different lifetimes; and are heavily interlinked and influenced by a variety of policies (Roelich et al., 2014).

Besides the adoption of these end-use technologies, their environmental performance in the context of buildings is of interest. Traditional life cycle assessment (LCA) methods are effective to assess the environmental performance of established systems. Environmental performance of buildings in general led to a number of studies assessing which type of buildings and which of their life cycle phase contribute most to environmental impacts (Bastos et al., 2014; Ramesh et al., 2010; Sartori & Hestnes, 2007; Säynäjoki et al., 2012; Sharma et al., 2011). However, one of their shortcomings is that they are based on steady-state situations usually excluding temporal aspects (Davis et al., 2009; Levasseur et al., 2010; Reap et al., 2008). A more dynamic focus is particularly interesting in the context of buildings as their lifetimes are rather long and technological changes - driven by technology adoption - during their operational phase are expected to influence LCA results (Collinge et al., 2012; Frijia et al., 2012). This research jointly addresses these issues by presenting an agent-based building-energy model linked to an LCA based on data changing over time.

The building-energy model aims to portray the building stock's energy demand and heating systems adoption patterns for a particular region in Austria. The regional energy demand from buildings is determined by the number of buildings, their respective age and size (i.e. building stock fluctuation), installed insulation (i.e. energy standard), the efficiency of the heating system, and the occupants' behaviour (i.e. room temperature, hot water, and electricity demand). Each individual of these aspects is dependent on the interplay between the technical characteristics of buildings, various policies, involved agents (e.g. architects, advisors, installers), socio-economic, as well as social and personal elements (e.g. attitudes, norms, social network) (e.g. Michelsen & Madlener, 2013; Neij et al., 2009). Modelling all these aspects with their full depth of actor interactions and decision-making would quickly lead to overly complex models (Knoeri et al., 2014). Therefore, this study concentrates on capturing the full complexity of heating system adoption decisions, while building stock fluctuation, envelope renovations, photovoltaic installations, and energy consumption behaviours are represented simplified. We specifically focus on heating system adoption decisions, also because environmental impacts or benefits of buildings' heat demand largely depends on the type of heating system installed.

The heating system adoption decisions are modelled as an agent-based model (ABM), since ABMs are able to capture the complex interactions between policy interventions, technical and social structure, and individual behaviour (Grimm & Railsback, 2005; Janssen and Ostrom, 2005). Homeowners' decision-making processes for heating system replacements and new installations are empirically operationalized (e.g. Knoeri et al., 2011) based on a systematic literature review, qualitative interviews, and a quantitative survey. Thereby, we focus on when and why homeowners decide for a new heating system, what agents are involved in their decision making process, and what factors determine their heating replacement and new installation decision.

The environmental impact of the building stock's heat demand during the operational phase of buildings is then assessed by applying a dynamic LCA approach. Within this approach, the results of the agent-based building-energy model (i.e. dynamic foreground system) are combined with LCA based on life cycle inventory (LCI) data changing over time (i.e. dynamic background system). This approach allows to analyse to what extent environmental impacts of heat generated with individual heating systems (i.e. fossil-fuel, biomass, thermo-solar, and heat-pump) change over time due to expected technology-driven dynamics. Furthermore, the difference of using static or dynamic LCI data when assessing environmental impacts of buildings stock's heat demand for the entire region is illustrated.

Such combination of methods allows for developing and assessing scenarios of the building stocks' energy demand and heating system transition for an entire region capturing the complex socio-technical interrelations typically found when it comes to energy demand of buildings. The focus is set on heating system adoption decisions implementing not only homeowners' behaviour, but motives and factors which influence their individual decision making process including other agents involved in this process.

The suggested integration of dynamic modelling and time-specific LCA has the potential to overcome limitations of prevailing LCA applications usually neglecting temporal information. Overall, the results of the study shed light on what policy instruments could be most effective in reducing environmental impacts caused by energy demand from buildings.

References

Bastos, J., Batterman, S., and Freire, F. 2014 Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon. *Energy and Buildings* **69**: 344–353.

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L., and Bilec, M.M. 2012 Dynamic life cycle assessment: framework and application to an institutional building. *The International Journal of Life Cycle Assessment* **18(3)**: 538–552.

Davis, C., Nikolić, I., and Dijkema, G. P. J. 2009 Integration of Life Cycle Assessment Into Agent-Based Modeling. *Journal of Industrial Ecology* **13(2)**: 306–325.

Frijia, S., Guhathakurta, S., and Williams, E. 2012 Functional unit, technological dynamics, and scaling properties for the life cycle energy of residences. *Environmental Science & Technology* **46(3)**: 1782–8.

GEA 2012 Global Energy Assessment - Toward a Sustainable Future, Key Findings, Summary for Policymakers and Technical Summary: Cambridge University Press, Cambridge UK and New York NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grimm, V. and Railsback, S.F. 2005 Individual-based Modeling and Ecology: Princeton University Press.

Grubler, A. et al. 2012 Policies for the Energy Technology Innovation System (ETIS), in Johansson, T.B. et al. (Editors) Global Energy Assessment: Towards a Sustainable Future: Cambridge University Press, Cambridge, p. 1665-1743.

Janssen, M.A., and Ostrom, E. 2005 Governing social-ecological systems, in Tesfatsion, L. and Judd, K.L. (Editors) Handbook of computational economics II: Agent-based computational economics: Elsevier, Amsterdam, The Netherlands.

Knoeri, C., Binder, C. R., and Althaus, H. J. 2011 An agent operationalization approach for context specific agent-based modeling. *JASSS The Journal of Artificial Societies and Social Simulation* **14(2)**.

Knoeri, C., Goetz, A., and Binder, C.R. 2014 Generic bottom-up building-energy models for developing regional energy transition scenarios. Paper presented at the 9th Conference of the European Social Simulation Association, Barcelona, Spain (01-05. September 2014).

Knoeri, C., Steinberger, J., and Roelich K. forthcoming End-user centred infrastructure operation: Towards integrated infrastructure service delivery. *Journal of Cleaner Production.*

Roelich, K., Knoeri, C., Steinberger, J. K., Varga, L., Blythe, P. T., Butler, D., Gupta, R., Harrison, G., Martin, C., and Purnell, P. 2014 Towards resource-efficient and service-oriented integrated infrastructure operation. *Technological Forecasting and Social Change (in Press).*

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., and Samson, R. 2010 Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science & Technology* **44(8)**: 3169–74.

Michelsen, C.C., Madlener, R. 2013 Motivational factors influencing the homeowners‘ decision between residential heating systems: An empirical analysis for Germany. *Energy Policy* **57**: 221-233.

Neij, L., Mundaca, L., and Moukhametshina, E. 2009 Choice-decision determinants for the (non) adoption of energy efficiency technologies in households. Paper presented at the Proceedings of the European Council for an Energy Efficiecy Economiy: La Colle sur Loup, France.

Ramesh, T., Prakash, R., and Shukla, K.K. 2010 Life cycle energy analysis of buildings: An overview. *Energy and Buildings* **42(10)**: 1592–1600.

Reap, J., Roman, F., Duncan, S., and Bras, B. 2008 A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment* **13(5)**: 374–388.

Sartori, I., and Hestnes, G. 2007 Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings* **39(3)**: 249–257.

Säynäjoki, A., Heinonen, J., and Junnila, S. 2012 A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. *Environmental Research Letters* **7(3)**: 034037.

Sharma, A., Saxena, A., Sethi, M., and Shree, V. 2011 Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews* **15(1)**: 871–875.

Wilson, C. et al. 2012 Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change* **2(11)**: 780-788.