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Dear Editors:

My co-authors and I are pleased to submit an original Research Article to *Energy Economics*.

TITLE

**A comprehensive, partial equilibrium
energy rebound analysis framework**

AUTHORS

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STATEMENT

I attest that this manuscript is our original work, that it has not been previously published in a journal, in whole or in part, and that it is not under consideration by any other journal. All authors are aware of, and accept responsibility for, the manuscript. The authors have no conflicts of interest.

RATIONALE

Amidst ongoing debates over the size and extent of energy rebound effects, energy efficiency measures are expected to contribute a key part of energy-related CO₂ emissions reductions in support of Paris Agreement targets, even while the world economy grows. Therefore, continued work on energy rebound theory and modelling is required to support energy efficiency modelling and policy responses.

The research gap we identified is that although work on rebound is now routinely cast in terms of microeconomic categories, microeconomic rebound theory is scattered across papers and lacks unification. In response, we develop a comprehensive, partial equilibrium rebound analysis framework, which includes emplacement, substitution, income, and macro effects. Further, we develop two

empirical case studies, of a car and an electric lamp, and obtain estimates for total rebound of 48 and 80%, respectively.

The paper contains four contributions. First, we develop the first comprehensive rebound analysis framework that accommodates embodied energy effects, maintenance and disposal effects, non-marginal energy efficiency increases, and non-marginal energy service price decreases. Second, we provide the first (to our knowledge) visualizations of rebound effects in energy, expenditure, and consumption spaces. Third, we create the first (to our knowledge) operationalized link between rebound effects on microeconomic and macroeconomic scales. Fourth, we provide tools for other researchers to calculate rebound for other EEUs with our framework.

From the development and application of the framework, we can draw three important conclusions. First, the car and lamp examples show that the framework enables quantification of magnitudes of all microeconomic rebound mechanisms, including direct and indirect locations for emplacement, substitution, and income effects. Second, the examples show that magnitudes of rebound effects vary with the type of energy efficiency upgrade performed. Third, the sensitivity studies enable evaluation of rebound sensitivities to important parameters, including for the first time the full emplacement effect and the macro effect. For the examples in this paper, total rebound is more sensitive to the price of energy, the elasticity of energy service demand, and the macro factor (k) than either the energy efficiency gain or capital costs of the energy efficiency upgrade.

REVIEWER SUGGESTIONS

- **Severin Borenstein**, E.T. Grether Professor of Business Administration and Public Policy in the Economic Analysis and Policy Group of the Haas School of Business at the University of California, Berkeley. Email: severinborenstein@berkeley.edu. His current research interests include the economics of renewable energy and economic policies for reducing greenhouse gases. His 2015 paper provides a foundation for our work:
 - Borenstein S. A Microeconomic Framework for Evaluating Energy Efficiency Rebound and Some Implications. *Energy J.* 2015;36(1):1–21.
- **Ines Azevedo**, Associate Professor, Energy Resources Engineering, Stanford University, USA. Email: iazevedo@stanford.edu. Her research interests are keenly focussed on energy rebound, with some of her papers providing foundations for this current paper.
 - Azevedo IL, Sonnberger M, Thomas B, Morgan G, Renn O. The Rebound Effect: Implications of Consumer Behaviour for Robust Energy Policies. International Risk Governance Council. 2013.
 - Thomas BA, Azevedo IL. Estimating direct and indirect rebound effects for U.S. households with input–output analysis Part 1: Theoretical framework. *Ecol Econ.* 2013;86:199–210.

- Azevedo IML. Consumer End-Use Energy Efficiency and Rebound Effects. *Annu Rev of Environment Resour.* 2014;39:393–418.
- **Reinhard Madlener**, Director of the Institute for Future Energy Consumer Needs and Behavior (FCN), Aachen, Germany. Email: RMadlener@eonerc.rwth-aachen.de. His research interests include energy economics, energy management, energy policy-making. He has a wealth of experience in energy rebound, which makes him a very suitable reviewer.
 - Madlener R, Alcott B. Energy rebound and economic growth: A review of the main issues and research needs. *Energy.* 2009 Mar;34(3):370–6.
 - Madlener R, Turner K. After 35 Years of Economic Energy Rebound Research: Where do we stand ? In: Santar. 2016. 1–26 p.
 - Colmenares G, Löschel A, Madlener R. The rebound effect representation in climate and energy models. *Environ Res Lett.* 2020;15(123010):1–35. 20-1.
- **Carey King**, Assistant Director and Research Scientist at the Energy Institute at The University of Texas at Austin, United States. Email: careyking@energy.utexas.edu. Dr. King has wide experience in energy and energy policy, spanning both engineering and economics, making him a good reviewer for this paper.
 - *The Economic Superorganism: Beyond the competing narratives on energy, growth, and policy.* Springer, 2021.
 - C. W. King. An integrated biophysical and economic modeling framework for long-term sustainability analysis: the HARMONEY model. *Ecological Economics*, 169C(106464):1–21, 2020.

KEYWORDS

- Energy efficiency,
- Energy rebound,
- Energy services,
- Microeconomic rebound,
- Substitution and income effects,
- Macroeconomic rebound

REPLICABILITY

A key requirement for Energy Economics is that the paper should be replicable. In our case, we have made sure our work is replicable. First, we provide the R-code packages and links for the reader. Second, we will make available our excel-based example sheets in a University of Leeds data repository, which has a permanent DOI link. Third, all data used in our examples are freely available in the public domain. Last, we have secured open access funds for the paper. If this submission moves to publication, open access will encourage its use and aid replicability.

Finally, we have worked hard to provide a concise, novel article that we believe will be of significant interest to your readership. It is keenly aligned to both the Aims and Subject Areas of *Energy Economics*, especially conversion and use of energy, regulation and taxation, and environment and climate. We thank you for your consideration of our work.

Yours sincerely,

A handwritten signature in black ink, reading "Matthew K. Heun". The signature is fluid and cursive, with the first name "Matthew" being more legible than the last name "Heun".

Matthew K. Heun