# Executive summary for Advancing the necessary foundations for empirical energy rebound estimates: A partial equilibrium analysis framework

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## Motivations underlying the research

Widespread implementation of energy efficiency is a key greenhouse gas emissions mitigation measure, but rebound can "take back" energy savings. However, conceptual foundations lag behind empirical estimates of the size of rebound. We posit that development of solid analytical frameworks for rebound is hampered by the interdisciplinary nature of the topic, involving both economics and energy analysis. As such, further progress overcoming interdisciplinary barriers to support development of conceptual foundations is both urgent and welcome.

## Short account of the research performed

In this paper, we help advance a rigorous analytical framework that starts at the microeconomic level of rebound and is approachable for both energy analysts and economists. We include emplacement, substitution, and income rebound effects and link them to macro rebound. We apply our framework to two examples, energy efficiency upgrades (i) from a gasoline-powered vehicle to an electric vehicle and (ii) from an incandescent electric lamp to a light-emitting diode electric lamp. In addition, we develop a series of novel graphs to show rebound paths through energy, expenditure, and consumption spaces.

The key contributions of this paper are development of the first (to our knowledge)

(i) rebound analysis framework that combines embodied energy effects, maintenance and disposal effects, non-marginal energy efficiency increases, and non-marginal energy service price decreases,

(ii) visualizations of rebound effects in energy, expenditure, and consumption spaces,

(iii) operationalized link between rebound effects on microeconomic and macroeconomic scales, and

(iv) open source tools to calculate rebound for other energy efficiency upgrades.

## Main conclusions

The work presented in this paper leads to four conclusions.

(i) The framework enables quantification of rebound magnitudes at microeconomic and macroeconomic scales, including direct and indirect locations for emplacement, substitution, income, and macro effects.

(ii) We obtained estimates of total rebound in two case studies: upgrades of a car (48%) and an electric lamp (80%). As expected, magnitudes of rebound effects vary with the type of energy efficiency upgrade performed.

(iii) For our two examples, total rebound is more sensitive to the price of energy, the elasticity of energy service demand, and the macro factor than either energy efficiency or the capital cost of the upgraded device.

(iv) Rebound is a headwind for efficiency-led reduction of both energy consumption and $CO_2$ emissions.

## Potential benefits, applications and policy implications

Laying solid conceptual foundations for rebound analysis leads to firmer quantification of rebound effect magnitudes, which is itself an important precursor to devising effective energy policies that would encourage energy efficiency, limit rebound effects, and reduce $CO_2$ emissions. With careful explication of rebound effects, clear derivation of rebound expressions, novel visualizations of rebound paths, and open source tools for quantification of rebound, we advance the analytical foundations for empirical estimates of rebound and facilitate interdisciplinary understanding of rebound phenomena toward the goal of enabling of more robust rebound estimates for sound energy and climate policy.