Economic input-output life-cycle assessment methods for estimation of indirect rebound effects

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A decrease in the price of energy services might occur then energy efficiency investment lead to net cost savings. In such cases, investments in energy efficiency may not yield expected benefits due to rebound effects. An increase in consumption of an end-use service is, called the direct rebound effect. Indirect rebound effects might also occur as a result of the rise in effective income or output production capabilities, the embodied energy in re-spending energy cost savings, and secondary effects such as longer-term shifts in the structure of the economy and reductions in the market price for energy due to the cumulative investments in energy efficiency. These direct and indirect rebound effects are together known as the economy-wide rebound effect, although some analysts consider also define the secondary effects as the economy-wide rebound effect. All of these effects, direct, indirect or economy-wide, can be studied in a short-term or long-term time horizon. In my research, I estimate the short-term indirect rebound effect for efficiency investments by residential households using economic input-output life cycle assessment (EIO-LCA).

In the literature, economy-wide rebound effects have been studied using macroeconomic models such as input-output life-cycle assessment (EIO-LCA) (Druckman et al., 2011; Chitnis et al., 2011; Howells et al., 2007; Thomas, 2011; Guerra and Sancho, 2010), computational general equilibrium (CGE) models (Guerra and Sancho, 2010; Saunders, 2010; Allan et al., 2006), and a variety of econometric and optimization models which are reviewed in (Sorrell et al, 2007). Input-Output (IO) models use a partial equilibrium framework in which prices are fixed and use linear, or Leontief, production functions, which do not allow for substitution between factor inputs. In their review, Sorrell *et al.* (2007) characterize the IO model as: " a very simple CGE that only applies, in its usual specification, when the supply side is, for some reason, entirely passive."

It should be noted that when used for life-cycle assessment of a particular product, IO models can represent the total upstream economic, energy, and environmental requirements of production. However, other lifecycle phases such as transportation, distribution, use, and disposal, must be modeled in separate processes and incorporated either into final demand or outside the EIO-LCA model. However, since the unit of analysis in this study is the annual final demand of a residential household, it does incorporate use-phase energy consumption or emissions through final demand for home energy and gasoline. In addition, the energy and emissions of the transportation and distribution phases of the household's consumption can be captured at first order by using a purchaser price IO-model, which incorporates wholesale and retail trade costs on top of a purchaser price model.

Despite the limitations of linear production functions, fixed prices, and fixed factors of production, IO models have several strengths highlighted by a handful of rebound studies, which are reviewed here:

1. The ability to represent a base case scenario without rebound effects, which when coupled with CGE models, can estimate long-term economy-wide rebound effects (see Guerra and Sancho, 2010, and Saunders, 2010),
2. The ability to represent residential demand for energy and the rebound implications of re-spending energy cost savings (Druckman, 2011, and Thomas, 2011),
3. The flexibility to directly represent the capital or other costs of efficiency (Allan *et al.*, 2006, Chitnis et al., 2011), and
4. The fixed price and capital stock assumptions of IO models make them especially useful for evaluation of rebound effects in the short (1-5 years) time frames of relevance for policy and business decision-making.

EIO-LCA models, or more generally, Leontief production functions, are useful in establishing a base case which depicts no direct rebound effects due to price elasticity, since prices are fixed. A CGE model with a more flexible production function which can depict price changes due to linkages between intermediate good and final good markets can then be used to simulate energy demand including short-term direct and indirect effects. Guerra and Sancho (2010) use this strategy to measure the short-term economy-wide rebound in Spain. Saunders (2008) argues that many commonly used production functions such as Cobb-Douglas or constant elasticity of supply (CES) either always predict backfire or are not flexible enough to depict the range of possible rebound magnitudes. Saunders uses Leontief production functions of the type used in EIO-LCA to depict the no-rebound case and compares it to a rebound-flexible translog production function over several decades to find short-term rebound effects of 60% and long-term backfire effects (Saunders, 2010). The challenge in these simulations is the calibration of production functions in terms of substitution between energy and other factors of production, the consistency of these elasticities with previous literature, and the depiction of technology change over time.

EIO-LCA models also useful for quantifying the indirect or re-rebound effect. The re-spending rebound effect, so named by Schipper and Grubb (2000), includes an income or output effect, in which increased income from energy cost savings leads to greater purchases of all goods by consumers and greater output production by firms (Sorrell, 2007). The income/output effect, coupled with estimates of the embodied energy of the lifecycle stages of goods, determines the energy implications of re-spending energy cost savings from efficiency. Hertwich (2005) demonstrates that the potential bounds of the re-spending rebound effect vary based on whether the energy end-use is a normal, inferior or luxury good, and on the relative environmental load of a reference technology, a cheaper efficient alternative, and re-spending. However, Hertwich does not consider the case of more expensive (in terms of capital cost) efficient technologies. Estimates of this re-spending effect have been calculated using engineering-economic models of the use phase of efficient appliances and re-spending on gasoline or increased appliance usage (Chalkley et al., 2002) and using EIO-LCA models of the embodied energy of production of typical bundles of national average household purchases in the U.K. (Druckman *et al*., 2011) and the U.S. (Thomas, 2011) using national surveys of household expenditure. These studies are unique in their focus on the rebound effects from efficiency in household consumption, rather than in industrial sectors. However, the capital costs of efficiency investments have typically been ignored in these studies with a few exceptions (Chitnis, 2011).

Yet, EIO-LCA models can be adapted to incorporate the capital costs of efficiency. If energy efficiency investments lead to a decline in the final demand for energy, as depicted in Druckman (2011) and Thomas (2011), they also lead to an increase in the final demand for capital goods, depending on the type of efficiency investment. For example, an investment in a hybrid vehicle could be modeled as an increase in the final demand for automobile manufacturing by the incremental levelized capital costs of the vehicle, and such research is currently underway. One would expect a lower rebound effect when capital costs are taken into account. A CGE study (Allan et al., 2006) that indirectly accounts for the cost of efficiency through an indirect change in the cost of labor, shows that rebound effects are reduced when taking the costs of efficiency into account, and verification with EIO-LCA models through a more transparent representation of capital costs of efficiency investments would be useful.

The fixed production factors assumption of EIO-LCA models is also a strength for studying rebound effects in the short term (<5 years), which is of most relevance for business and political decision-making. In the short-term, it seems unlikely that much substitution between the main factors of production (capital, labor, energy, materials) will have occurred. The utility seeking to justify the cost-effectiveness of demand-side management efficiency programs to public utility commissioners or the policymaker seeking to evaluate compliance with an energy efficiency standard, should be interested in analysis on the expected rebound effects in elections- or business-cycle time-frames due to respending (as well as price effects). Likewise, energy modelers should incorporate rebound effects due to income/output elasticity, price elasticity, and embodied energy, if they have not already done so. EIO-LCA models are a useful, simple, and transparent method for estimating rebound effects, especially due to respending.

Given the strengths of EIO-models, I have used it to estimate the indirect rebound effect for electricity and gasoline efficiency investments by U.S. households of various income brackets. I estimate upper and lower bounds of the indirect rebound effect based on complete respending in electricity or complete savings. I also plan to incorporate the levelized annual cost of typical household efficiency investments in various energy end-uses. In addition, these simulated indirect rebound effects will be compared with parametric direct rebound effects. Sensitivities to key input parameters such as grid emissions factors, energy prices, and regional variation in rebound effects in the U.S. will also be explored, to inform on the expected benefits on energy efficiency policies.

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