Author response to referee comments

Energy, expenditure, and consumption aspects of rebound, Part I: Foundations of a rigorous analytical framework (23-007)

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Part	Comment #	Comment	Authors' response
1 - Framework	1	I wonder whether there needs to be a discussion of where the boundaries of what we call "rebound" should be drawn? Without checking the literature, but aware that Steve Sorrell (who is not this referee) did a systematic review for UKERC some years ago (which I read at the time), I'd think of it as "the reduction in energy savings, compared to engineering estimates, due to behavioural changes", and might add a component for the difference between "factory-measured" and "as imperfectly fitted" savings (with unchanged behaviour). Embodied energy is certainly important (and a big part of the life cycle literature), but is it "rebound"? The definition just given(with the caveat that preceded it!) would suggest not. That certainly doesn't mean it is! Should maintenance energy be included when calculating the "engineering estimate"?	Thank you for this comment, which asks about the merits of including embodied and maintenance effects within our rebound framework. Given our goal of including as many rebound channels as possible, it makes sense to include these effects. Your comment prompted a mini literature search to double-check what others had done in the past. • Embodied rebound: We found that Steve Sorrell's 2007 main report does include embodied rebound, as he writes, in Box 1.2, that embodied energy is the "indirect energy consumption required to achieve the energy efficiency improvement, such as the energy required to produce and install thermal insulation". Incidentally though (and good recall!), Sorrell does indeed include a typology which sets out rebound as the engineering estimate of savings vs. actual energy savings in that same Box 1.2. Further, we found that embodied rebound is quite widely referred to in rebound typologies, including Borenstein (2015) – footnote 5, and Saunders et al. (2021) . • Operation and maintenance: This is probably less common (versus embodied rebound) but is still reasonably prevalent. Examples include Sorrell et al. (2009), Borenstein (2015) – footnote 37, and Sorrell et al. (2020). • Emplacement effects: your question also made us also think more broadly about emplacement effects, which is a new term that we introduced to encompass embodied energy (emb), operations and maintenance (OM), and disposal (d) activities. We needed a place distinct from substitution and income microeconomic effects to calculate rebound according to our calculation framework. Re-reading, we feel that we haven't done as well as we couldn't have done to highlight this new term and its reason for being introduced. Bringing these points together, we have made amendments that hopefully better introduce/explain our introduction of the 'emplacement' effect, and at the same time provide supporting references for the embodied, operations and maintenance, and disposal rebound effects in Section 2.1.

			Near the start of Section 2.1 the existing text said: "Microeconomic rebound occurs at the level of the single device and its owner and in our framework comprises three effects: an emplacement effect, a substitution effect, and an income effect, each of which partitions direct and indirect rebound effects. All combinations are possible. We then add the following text: • "Emplacement" is a new term we introduce to collect effects associated with installing higher-efficiency devices, including (i) embodied energy of their manufacture (emb), (ii) operations and maintenance (OM), and (iii) disposal (d) activities. Although none of the embodied, operations and maintenance, or disposal effects are new (see Borenstein (2015, footnote 5, p. 3), Saunders et al. (2021), Sorrell et al. (2009), Borenstein (2015, footnote 37, p. 16), and Sorrell et al. (2020)), we separate them from substitution and income microeconomic effects (Table 1) to calculate rebound according to the steps in our framework. So, overall, thanks again for this comment, its made us both provide references for the embodied and O&M effects and also provide a better introduction to the new 'emplacement' term.
1 - Framework	2	The authors also convert the stock variable of initial embodied energy into a flow by simply dividing it by the device lifetime – it's much more usual in economics to use some kind of discounting, certainly when it comes to costs appearing in budget constraints.	Thank you for this suggestion. Although it was rather painful to implement, we have fully included discounting in the budget constraint throughout both papers. Implementing this suggestion involved major surgery in the papers and in the ReboundTools R package, but we believe the papers and the software are more general and therefore better for it. Our approach is as follows: * We annualize costs, derived from the net present value of all future costs with a positive discount rate (r). * Apply discounting to ONLY the financial aspects of the framework. Energy is never discounted. * Variables for capital and disposal cost rates (C_dot_cap and C_dot_d) remain their undiscounted versions. * Discounting is applied via multiplicative terms R_alpha and R_omega for the capital cost and disposal costs, respectively, in the budget constraint. See Appendix B.1 of Part I for details. * Proved that R_alpha and R_omega go to 1 when the real discount rate (r) goes to 0.0, as expected. See Appendix B.1 for proofs. * Discounting applied to capital costs is tantamount to assuming the device owner takes out a loan to purchase the device, thereby introducing loan payments to the framework and reducing spending on other goods and services as a result.

			* Since the annualized cost includes financing costs, we removed financing costs from the car price reported in the earlier version of the paper. * Furthermore, we no longer need to assume the device owner sells the car after 7 years of its 14-year life, thereby simplifying calculations. * Discounting applied to disposal costs is tantamount to assuming the device owner earns interest on saved money, thereby reducing costs for disposal and allowing higher spending on other goods and services. * Further, we now include a sensitivity study on discount rate (r) in the appendix for the results paper. The sensitivity study shows that, relative to other parameters, rebound is rather INsensitive to the assumed discount rate for the examples in the paper. The effect of all the changes necessitated by this improvement is given by the following table: 　　　　　Car　Lamp Previous 47.2% 67.1% Updated 56.2% 67.0% Most of the difference in the car example is caused by other changes besides discounting, such as removing financing costs from the car price. We trust the reviewer will be satisfied with the generalization brought about by our response to this important suggestion.
1 - Framework	3	I think the macro effects, on the other hand, probably do fall into the "rebound" category, and are well within the spirit of Jevons' original remarks, although he long preceded Keynesian multipliers! However, rather than using multipliers alone, I think the authors need to think about the effects of reducing the demand for energy on its price in a world where supply is not perfectly elastic. That effect is likely to be much more direct, and hence easier to measure, than the indirect and longer-term effects of greater energy productivity or real-terms consumer spending. A partial	We thank the reviewer for encouraging us to include an energy price rebound effect into our model. We had initially excluded such an effect since its magnitude depends on share of consumers in an economy adopting the device as it is determined by the change in aggregate, not household demand. Following the reviewer's advice however, we include a simple partial equilibrium model of the energy sector: it computes the decline in the energy price as a function of the share of consumers adopting the energy efficient device upgrade and the price elasticity of supply of the energy carrier in question. We derive the model in Part I where we introduce it briefly alongside the other macro effect, and then discuss it in section 3.2. In Part II, we calculate its magnitude for the two examples for a plausible range of supply elasticities and for all possible adoption shares. The calculations show that, depending on the circumstances of the specific upgrade, the energy price effect could either add little rebound or substantially enlarge it.

		equilibrium model of the energy sector ought to be sufficient to capture the size of such price changes, which can then be fed into the rest of the analysis.	
1 - Framework	4	I'm still slightly sceptical about the importance of explicitly coping with non-marginal price changes. There's something about this at the very end of the online appendix to part II, but I'd advise putting a sentence into the paper itself that says how important this is, in terms of how much it changes the rebound effect, relative to the 0-100% scale. Even without the numerical estimates that are coming in part II, you can look forward to the result when you have the discussion of the contribution you're making.	We are grateful to the reviewer for raising the relevance of non-marginal price changes for rebound, which allowed us to revisit this topic and make changes to both manuscripts (Part I and Part II). We agree that the importance was perhaps slighlty overstated in the abstract and introduction and in response removed it from the list of main contributions and instead mention it under further contributions. We also follow the reviewer's advice to hint at the relevance of the exact rebound in Part I and calculate the difference in Part II. We find, in Table 14 of Section 4.4 in Part II, that both substitution and income rebound are different between the CES and CPE models. We also note that the importance of not using the approximation depends on the specific case. Table 14 and its discussion also include the satiated demand case. Again, we are grateful to the reviewer for raising this point as it allowed us to bring out the case-dependent relevance of approximating the substitution effect using a constant price elasticity.
1 - Framework	5	While the authors point out that other micro models of consumer behaviour are available, the one they've chosen has the serious weakness that the income elasticity of demand is inevitably equal to one. We know that a lot of energy services have an income elasticity of less than one, so this matters. There's an open question of whether getting the income elasticity or the substitution effects wrong is going to be a bigger problem. I'm not suggesting that the authors add the fully worked-out answer to this paper, but it needs to be acknowledged – and there could (should) be some basic calculations in part II.	Thank you for this comment. In response, we thought about non-homothetic utility models, realizing that the bounding case occurs when consumption of the energy service is already satiated. Under those condistions, the device owner will spend all income on other goods. We derived a new rebound expression for the extreme (satiated) case and added text in both Part I and Part II as discussed below. Part I After "However, this framework could accommodate non-homothetic preferences for spending across the income effect (turning the income expansion path into a more general curve instead of a line).", we now add this text: * Demand for certain energy services could satiate as consumers become more affluent, implying income elasticities of the energy service of less than one \citep{Greening2000}. At the lower bound, the consumer spends all income after the substitution effect on other goods and none on the energy service, choices that serve to reduce rebound due to typically lower energy intensity of other goods compared to the energy service.% \footnote{

In principle, the energy service could be an ``inferior good'' whose consumption declines as incomes rise. However, energy service elasticities of income have been estimated to be positive over the long run, so we do not expect the inferior good case to be relevant \citep{Fouquet2014}.
}

Thereafter, we provide direct and indirect rebound expressions for the extreme non-homothetic cases.

• In the section on the direct income effect, we add "Under a non-homothetic utility model, the bounding condition is satiated consumption of the energy service such that as the device owner becomes richer, none of the income ($\rasub{N}$) is spent on more of the energy service, and thus $Re_{dinc} = 0$ would occur."

• In the section on the indirect income effect, we add "Under the bounding satiated utility model, all income ($\rasub{N}$) is spent on other goods, and indirect rebound becomes simply $Re_{iinc} \equiv \frac{\rasub{N} I_E}{\Sdot}$."

Part II

We added new text about non-homothetic utility models in Section 2.2.3 (The consumption plane).

• "Under non-homothetic utility models, the income expansion path will be closer to vertical in the consumption plane, as the device owner spends more net income ($\rasub{N}$) on other goods and less on the energy service. In the limit, consumption of the energy service is already satiated, so net income is spent completely on other goods, resulting in a vertical income expansion path."

Finally, we added a new section in Section 4 (Discussion) entitled Comparison of CES with satiated and constant price elasticity (CPE) utility models. (The new section is too long to reproduce here.) The section contains a table that shows the numerical effect of assuming the extreme, namely that the device owner is already satiated in terms of energy service consumption. Interestingly, the car example shows some change when assuming satiated consumption of the energy service, while the lamp example does not. The reason is interesting and visible in Fig. 7. In the CES utility model, there is almost no income-effect spending on more of the energy service. And the path between the ^ and - points is already nearly vertical.

			Thanks again for this insightful coment. It caused us to look more closely at the utility model and enabled deeper explication of the two examples.
1 - Framework	6	My overall conclusion is that the paper does make a contribution, but I think it's less important than the authors claim.	Thanks for this comment and for noting the contribution made by the papers. Upon further review, we see places where our prose may have sounded grandiose. So we take your comment to indicate that we should tone things down a bit. Changes we made include: Part I: * Title: Added the word "Foundations" to suggest that we are laying foundations for a better analytical approach to rebound. * bring clarity to the field --> help advance clarity in the field * We endeavor to bring clarity to the field --> We endeavor to help advance clarity in the field * By so doing, we enhance clarity in the field --> By so doing, we help advance clarity in the field * we attempt to bring further clarity to rebound analysis --> we help advance clarity in rebound analysis * We develop the first (to our knowledge) rebound analysis framework that --> We develop a rebound analysis framework that * development of the first (to our knowledge) rebound analysis framework that --> development of a rebound analysis framework that * the first operationalized link between --> an operationalized link between * Another novel contribution of this paper (in addition to the framework itself) is the first operationalization of the macro rebound multiplier idea. --> Another contribution of this paper (in addition to the framework itself) is operationalization of the macro rebound multiplier idea. Part II: * To improve clarity in the rebound field, we developed --> To help improve clarity in the rebound field, we developed * to support our goal of bringing clarity to the process --> to support our goal of helping to advance clarity for the process * to bring clarity to --> to help advance clarity of * adding conceptual clarity to the field of energy rebound --> helping to advance conceptual clarity in the field of energy rebound * we advance clarity in the field of energy rebound --> we help to advance clarity in the field of energy rebound * The key contributions of this paper are (i) development of the first (to our knowledge) mutually consistent and numerically precise visualizations --> The key contributions of

			this paper are (i) development of mutually consistent and numerically precise visualizations
1 - Framework	7	I think my only "specific" point is that the budget constraint (eq. 4) would normally be written in terms of the general quantities of energy, other consumption, and so on, rather than solely in terms of the starting point (o superscript variables) – as written, it doesn't say anything about whether the other expenditure combinations have to add up to anything.	Thanks for this comment. The equation in question shows the original consumption of the energy service as $C\_dot\_s\_orig$ which is simply the product of the original price of the energy service (p_s_orig) and the original rate of consumption of the energy service ($q\_dot\_s\_orig$). We added a new equation beneath the equation in question where $p\_s\_orig * q\_dot\_s\_orig$ is substituted for $C\_dot\_s\_orig$. Similarly, $p\_o\_orig * q\_dot\_o\_orig$ is substituted for $C\_dot\_o\_orig$. We trust this addition addresses the concern.