The Rebound Effect and its Representation in Climate and Energy Models: A Review

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Presentation Outline

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1.1 Energy efficiency improvement as technical change:

- Energy efficiency improvement as **zero-cost breakthrough**
- Energy efficiency improvement as **heterogeneous policy-induced improvement** (Het-PI):
    1. **Price-induced instruments**
    2. **Command and control instruments**
    3. **Policy-induced improvements**

1.2 Energy efficiency improvement as change in preferences (change in consumer patterns)

- **Change in preferences** is not seen as a potential source of undesirable outcomes, but is consciously placed in order to achieve **desired better outcomes** and **consistency** in time.
- Including a lagged variable in studies **to capture inertia in energy prices** can help to mitigate correlation problems and at the same time **better reflect behavioral change / consumer behavior**.

2 Rebound effect formulations

Physical / economic channels and aggregation to represent energy to parse the rebound effect include:

1. Energy use as the **explicit representation** of energy efficiency improvement.
2. Energy use as an **explicit representation of an economic indicator**.
3. **Implicit energy efficiency**, using the own-price elasticity of energy as a proxy for the rebound effect.

Short-term modeling: Rebound effects include **changes in energy service demand** while holding capital or investments constant.

Long-term modeling: Possible incorporation of **laws of motion** for capital costs, savings, scrappage, crowding effects, and / or increasing market saturation of appliances.

3 Modeling the rebound effect

Modelers seek to get a closer look at how energy is being consumed in **real settings** by collecting data to use in models, and / or studying **treatment effects**:

1. Representation of **energy efficiency improvement**
2. Mathematical representation of the **rebound effect**
3. Economic theory, assuming a choice faced by a **representative agent** (consumer / producer / prosumer)
4. Include a degree of **heterogeneity of representative consumer and / or firms**

Our review has grouped energy and macroeconomic studies under the following **4 categories**:

- Structural models
- Econometric models
- Simulation models
- Integrated assessment models (IAM)

We present general assumptions for each type of model, and report on the EEI and RE representation and results in recent studies.

3.1 Structural models:

- Include **preferences and technology**, using observed **past behavior** (characteristic of *ex-post*, often econometric studies) to calculate **fundamental parameters**
- Most common means to calculate direct rebound effects (Eq. (1) to (3))

$$\Delta\varepsilon = ES/E > 0; \quad (1)$$
$$DRE = \eta_\varepsilon(ES); \quad (2)$$
$$DRE = 1 + \eta_\varepsilon(E); \quad (3)$$

3.1.1 Energy system structural models:

- Adoption of **industrial (or household) production function** (1st- or 2nd-order approx.)
- Identifying the ***substitution (output) effect and income effect for consumption (production)*** by use of **decomposition methods** (i.e. implicit function theorem) for calculating **elasticities**.
- Other sets of structural models represent **household demand consumption**, and allow to compute **direct + indirect rebound effects** (i.e. almost ideal demands (AIDs) or linearized AIDs with multi-stage budgets, linear expenditure systems (LES), direct addilog (DA), indirect addilog (IA), or double-log (DL) system)
- Parameters are obtained using **linear or non-linear econometric methodologies** (i.e. OLS, dynamic OLS, feasible GLS, NLS, etc.). Usual inputs are: energy (or energy commodities, services), capital, labor, and materials.

3.1 Structural models (2/2)

3.1.2 Economy-wide structural models:

- **Aggregated production functions (APFs)** using **Solow's residual** can also be used to approximate **total energy and GHG rebound effects** at national levels, as represented in eqs. (4) and (5).

$$DRE = -\eta_{P_E}(E); \qquad (4)$$

$$DRE = -\eta_{P_{ES}}(ES); \qquad (5)$$

- Assumption that **parameters remain unchanged**, to predict the responses to possible economic system changes, including those that have never happened before.

- Convenient to be used **to conduct welfare calculations**. Nonetheless, the major concern is that the **use of an "elaborate superstructure"** will provide results driven by the model rather than the data.

3.2 Econometric models:

- **To avoid restrictions** imposed by ***ex-post* structural forms** as in structural models, empirical modelers usually turn to **reduced-form statistical *ex-post* estimations**.

- Econometric studies represent the rebound effect in two broad categories, which vary according to the aggregation level of study:

  1. **Energy systems** that compute the direct rebound effect.
  2. **Economy-wide contexts** to calculate a total, national or sectoral rebound effect.

3.2 Econometric models (2/4)

3.2.1 Energy system econometric estimations:

- Categorization as ***ex-post* estimations** and calculated using **regression analysis**, generalized linear models, ARIMA, vector autoregression, and cointegration.
- Solved by using **time-series data**, cross-section analysis, panel data, and stochastic frontier functions.
- Less common: instrumental variable (IV) estimators, difference-in-difference estimators, and field quasi-experimental methods.
- More recently, **machine learning (artificial intelligence algorithms)** is being used in econometric estimations.

- Advantages:
  - ✓ Can account for casuality effects
  - ✓ Derive more robust results (but exogenous variables should be carefully controlled)

3.2 Econometric models (3/4)

3.2.2 Macro-econometric models:

- Despite difficulties in attaining a good degree of identification with reality, these **post-Keynesian *ex-ante* models** might perform useful **forecasting and policy analysis** (when an effective existing rule prevails).

- **Macro-econometric and non-equilibrium models** (e.g. global dynamic E3ME or NEMESIS) have been used to asses co-benefits and trade-offs of policy scenarios in European economies using **multiple sets of computable econometric equations**.

The E3ME model

3.2 Econometric models (4/4)

The E3ME model:

- Rebound effect is modeled in two parts: the **direct rebound** effect (eq. (2)) is taken from the **PRIMES bottom-up model** (an energy system model), and this is then used to calculate the **endogenous indirect rebound effect** and the **economy-wide rebound** effect (using eq. (4)), derived from the **input-output structure** of the model.

$$DRE = \eta_{\varepsilon}(ES); \qquad (2)$$
$$DRE = -\eta_{P_E}(E); \qquad (4)$$

- **Inputs** of the model are **shared with other models** such as the **PROMETHEUS** (fossil fuels and import prices) and **GEM-E3** (macroeconomic and sectoral projections).
- Main assumption w.r.t. energy efficiency is that **rising fuel prices will stimulate technological innovation and boost growth** of the world economy, thus the **endogenous representation of technological change** also has implications for the calculation of the rebound effect.
- Allows **varying returns of scale and nonlinear substitution**, and avoids the representative agent assumption.
- Nonetheless, **no allowance of substitution** between cheaper energy services and other inputs within production, and **embodied energy representation.**

3.3 Simulation models (1/5)

3.3.1 Energy system simulation models:

Input-output (**IO**) models and **environmentally-extended input-output models** (**EEIO**):

- Most comprehensive studies using this methodology use **estimates of direct rebound effects** as inputs.
- These *ex-post* static models allow the calculation of **indirect rebound effects** as cross-price elasticities for *n* goods (or *n* services).
- Following this estimation, **total rebound effects** are computed as represented in eq. (4).

$$DRE = -\eta_{P_E}(E); \quad (4)$$

- Most studies have focused on studying **indirect rebound effects on the consumption side**. These models assume that **constant returns of scale**, sectors producing **homogeneous goods and services**, and outputs are created with **constant and fixed proportions of inputs** (linear representation).

3.3 Simulation models (2/5)

3.3.1 Energy system simulation models:

- Moreover, cross-price elasticities of other goods can be modeled as constant or variable, and **re-spending** is usually assumed to be proportional in each good and service.
- Widely used data inputs: **Consumer Expenditure Surveys**, **Eora data, EXIOBASE**, data from the **Global Trade and Analysis Project (GTAP)**, and the **World Input-Output Database (WIOD)**.

- Modeling RE with an EEIO model, **Thomas and Azevedo (2013)** found that:
  - **IREs are inversely proportional to DREs** and
  - bounded by consumers' budget constraints,

  developed risk and vulnerability indicators for rebound effects.

3.3 Simulation models (3/5)

3.3.2 Macroeconomic simulation models:

Computable general equilibrium models (CGE) – Our approach

- Energy efficiency improvements are modeled as **exogenous autonomous energy efficiency improvement (AEEI)** and energy-augmenting, or endogenous technical change as latent variable approach of policy-induced type
- RE is calculated using eqs. (7) and (8)

$$R = 1 - \frac{AES}{PES}; \qquad (7)$$

$$RE = \left[1 + \frac{\dot{E}}{\alpha\gamma}\right] \cdot 100; \qquad (8)$$

- **Decomposition of energy and GHG rebound effects** from partial to general equilibrium
- **Parsing RE in direct and indirect partial equilibrium components** by setting all prices fixed except for the energy sector or service in analysis
- **General equilibrium component** is calculated via **commonly used channels**: price, growth: sectoral allocation, labor supply and growth: fiscal stimulus
- **Total RE:** obtained by summing the partial equilibrium components + the general equilibrium component

3.3 Simulation models (4/5)

3.3.2 Macroeconomic simulation models:

We checked the **adaptation and tailoring of models** for relevant interactions that might potentially impact on calculations of energy and GHG rebounds:

(1) Balance of trade (imports/exports)

(2) Technological change vs. economic expansion

(3) Imperfect competition

(4) Unemployment (labor market representation)

(5) Capital formation

(6) Dynamic adjustment of long-time frames

(7) Detailed treatment of energy supply

(8) Energy consumption

3.3 Simulation models (5/5)

3.3.2 Macroeconomic simulation models:

For each aspect, we find that:

(1) **Armington's CES imperfect substitution** was able to include an energy efficiency improvement representation.

(2) **Most models do not integrate adjustment of capital/labor growth** (or decline) with regard to energy efficiency improvement.

(3) Revised models assumed **perfect competition**.

For (4) and (5), **mobile representation of capital** between national sectors, investments, and labor increase gradually.

(6) **Recent models are not only dynamic**, such that they capture consumer's responsiveness including consumer response to price changes in time, but are **also regional-specific** (or spatial CGE models).

(7) To represent energy and non-energy goods, **CES / Cobb Douglas functions** are commonly used and inputs in the **energy sector** are usually modeled as **Leontief composites**, with no possibility of substitution, in RE studies assessed in this overview.

(8) While **energy efficiency improvement in TFP** has **not commonly** been **modeled**, it is has been included from **one consumer aggregate** with no possibility of substitution or CES / Klein-Rubin utility preferences, to **bottom-up representations** that capture consumer heterogeneity + distributional impacts.

3.4 Integrated assessment models (IAMs) (1/2)

Main types of *ex-ante* IAMs:

1. Detailed process (DP) IAMs
2. Benefit-cost (BC) IAMs

Main difference:

- **DP IAMs** are more disaggregated models that use economic valuation or physical projections to provide forecasts of climate change impacts at detailed sectoral or regional levels.
- **BC IAMs** represent sectoral (or regional) aggregation functions and climate change mitigation costs into a single economic metric, whose main goal is to analyze potentially optimal climate policies.

3.4 Integrated assessment models (IAMs) (2/2)

Advantages:

- ✓ Models allow **flexibility about the achievement of GHG emission reductions**, results in lower mitigation costs across all economic assumptions.
- ✓ **DP IAMs** identify and directly measure impacts on sectors, regions and ecosystems in more detail, providing insights of trade-offs between mitigation and adaptation strategies on global scales (→ useful for international negotiators, and national / regional decision makers).
- ✓ **BC IAMs** are helpful to highlight critical issues in the understanding of the cost-effective-ness of climate change policies, while incorporating new scientific findings into projections.

Disadvantages:

- – Too much flexibility can be detrimental to models.
- – Delays in implementing mitigation policies would result in increases in total discounted costs of meeting particular global GHG concentrations

4 Model identification: a trade-off between theory and reality (1/5)

4.1 Ex-post studies:

- **Structural functions** are the most often used methodology on production side.
- On the **consumption side**, the maginitude of the rebound effect is sensitive to model specification; **modeling energy services** as an alternative to energy commodity models is advised.
- The distinction between **consumption and production direct rebound effect** is of great relevance.
- Recent econometric models on energy systems have evolved to include **data from field experiments**, use **randomized controlled trials**, and study **causality effects** on the consumption side.
- There are **fewer studies on the production side** using these up-to-date methodologies.
- Aforementioned studies provide valuable **insights on the effectiveness of energy efficiency policies** and on the rebound effect.

We find that ***ex-post* studies** that put emphasis on reality depiction (policy and/or zero-cost breakthrough) are of high importance in providing empirical evidence that could serve as an **input for *ex-ante* studies**, in order to feed accurate parameters to *ex-ante* studies.

4.1 Ex-post studies

Studies reviewed: 26

Energy rebound effect:

Ø 66%
Min -22%
Max 334%
σ 79%

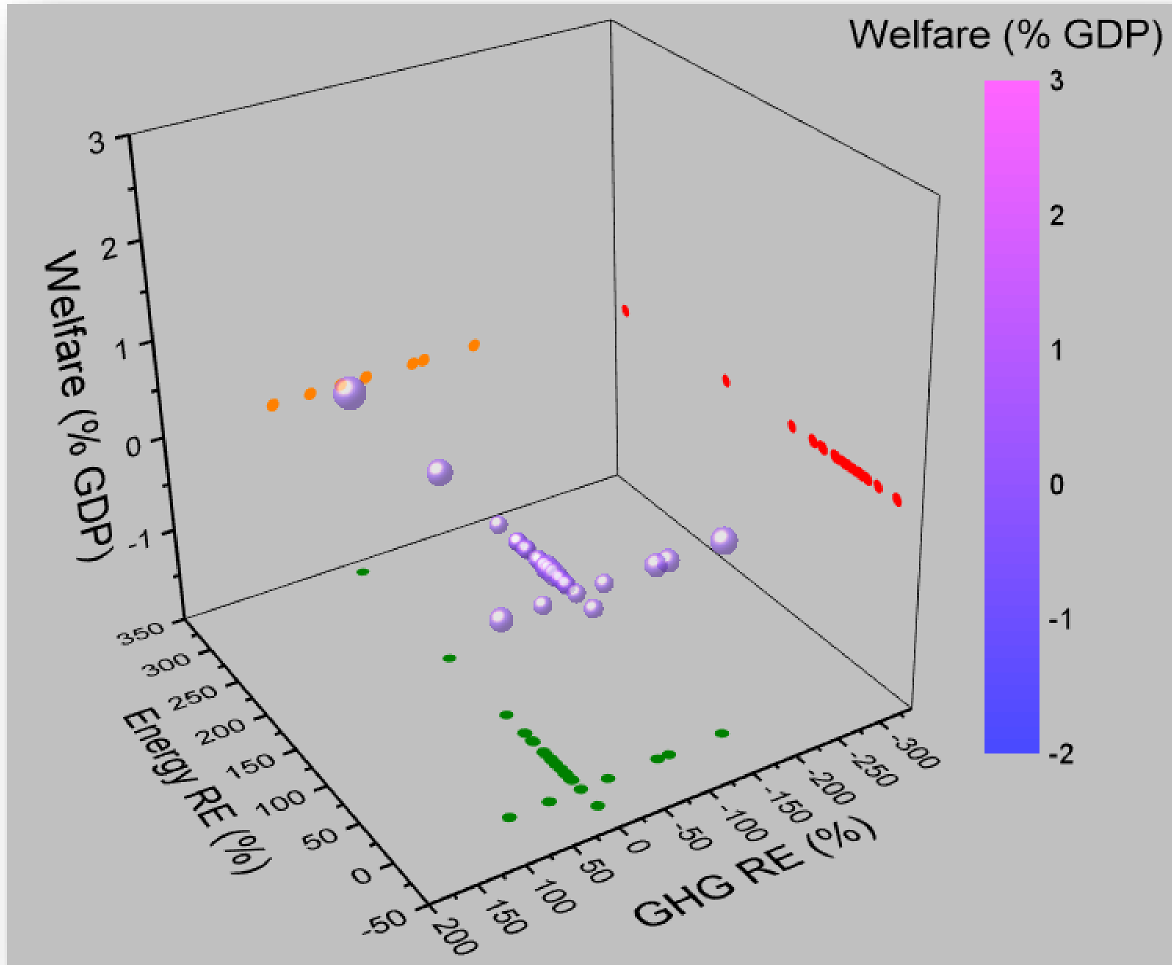
GHG rebound effect:

Ø -38%
Min -161%
Max 78%
σ 83%

Welfare effects (GDP):

Not computed

Results on ex-post studies



4 Model identification: a trade-off between theory and reality (2/5)

4.2 Ex-ante studies:

- Rely on **structural forms** or econometric estimates for the representation of consumer or producer choices.
- On the **production side**, it is proposed to revise the adequacy of CES functions to represent the nested production function, and to better match the energy-augmenting technical progress paradigm.
- With regard to the **elasticity parameter**, studies show that a low elasticity of substitution between energy and nonenergy inputs, would result in a larger general equilibrium RE component.
- In contrast, other studies have found that **low elasticity of inter-fuel substitution** would reduce the magnitude of the energy rebound effect.
- With regard to the **intensity of the energy of sector**, rebound effects may be larger if energy efficiency improvements are found or implemented in these sectors. In addition, the larger size of the other sectors not affected by energy efficiency improvements could also increase the rebound effect magnitude.
- With regard to **growth expansion**, it is recommended to examine trade-offs between economic expansion and energy efficiency improvement.
- Finally, **investigating rebound effect behavior in time** is of importance, as it is theoretically possible that **long-run elasticities** are lower than **short-run elasticities**, while empirically, Lu et al. (2017) finds that the long-run energy rebound effect diminishes.

4.2 Ex-ante studies:

- On the **consumption side**, studies find that a **more elastic elasticity of substitution** between energy and non-energy goods determines a **larger partial equilibrium component** which dominates the general equilibrium component.

- In contrast, if the aforementioned parameter tends to have a **low elasticity of substitution**, it would result in **small energy rebound effects** due to consumer price unresponsiveness.

- More recently, **heterogeneity** has played an important role in studies, disaggregating **specific energy-intensive and less energy-intensive energy services**, and including the representation of **durable goods / investments within energy service sectors** could provide **more accurate policy advice**.

4.2 Ex-ante studies

Studies reviewed: 19

Energy rebound effect:

Ø 49%
Min -0.1%
Max 98%
σ 22%

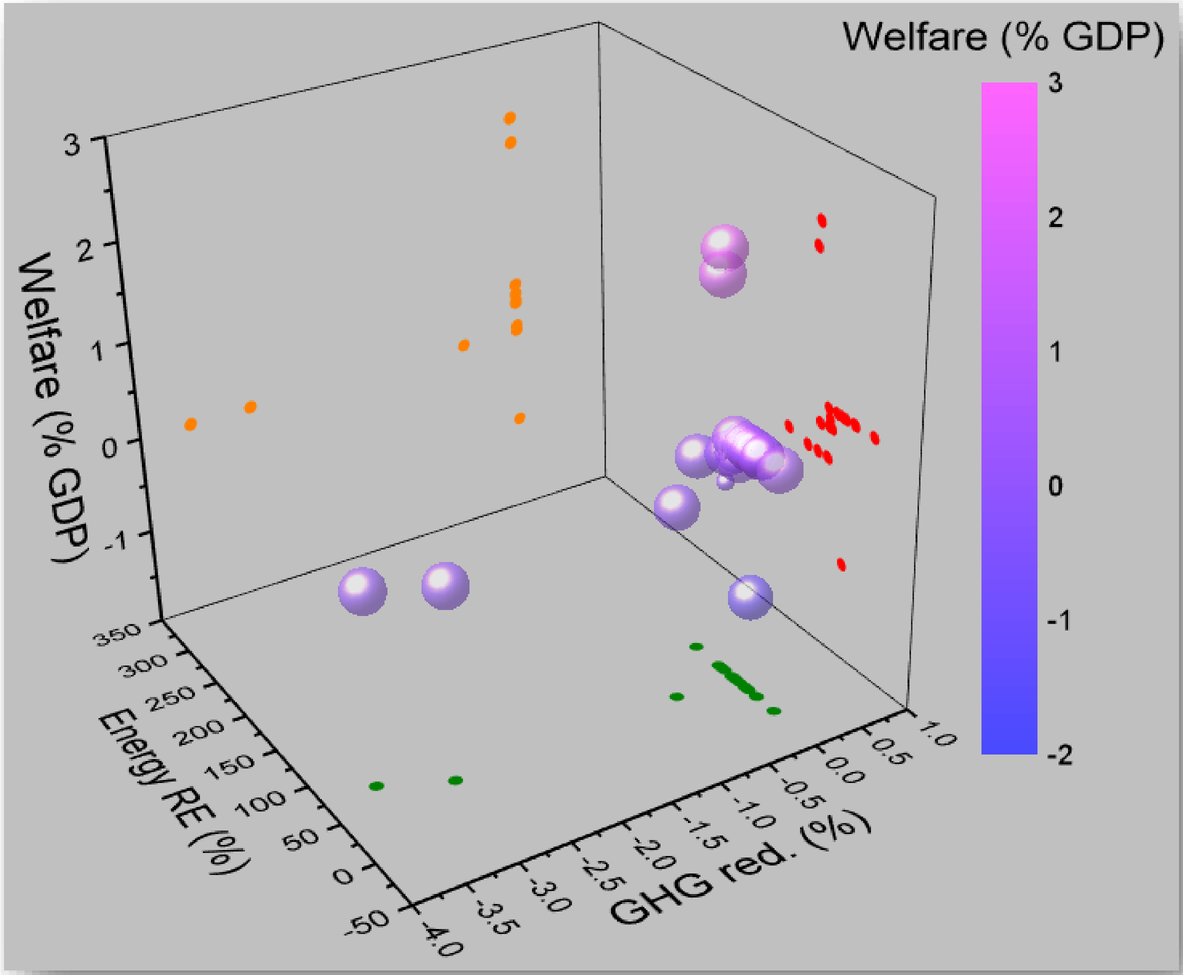
GHG rebound effect:

Not computed

Welfare effects (GDP):

Ø 0.4%
Min -1%
Max 2.25%
σ 0.7%

Results on ex-ante studies



4 Model identification: a trade-off between theory and reality (4/5)

4.3 Combined insights:

- **Taking both sides into account**, studies validating elasticities with historical data and the use of more sophisticated methods (i.e. causality ident.) and sensitivity analyses would improve the reliability of studies.
- **Explicit and endogenous representations of energy efficiency** improvements could also reduce bias in estimates.
- Looking at the **general equilibrium component**, supply and demand effects should be considered, as should the interaction of energy efficiency improvements on both sides.
- The ***status quo* of the data** should be **checked against assumptions** of the year when technical energy efficiency improvement is introduced (to take into account both innovation phases and also diffusion and approximation to saturation). If **policies** are already in place, this should be modeled because high initial levels of energy efficiency improvements in place could result in higher GHG rebounds.
- Furthermore, the **dynamics of the incorporation of energy efficiency improvements** in primary and / or secondary energy would provide further insights.
- Another branch of the RE study includes **externalities** (e.g. pollution effects).

In general, models could include **locational aspects, temporal aspects, and group targeting** to check distributional effects when price is endogenous.

Ex-ante studies can also be used to monitor rebound effects in the economy, not just for forecasting (e.g. using now-casting or back-casting methods in CGE models).

4.3 Combined insights (1/3): All Studies

Studies reviewed: 118

Energy rebound effect:

Ø 58%

Median 49%

σ 58%

GHG rebound effect:

Ø 43%

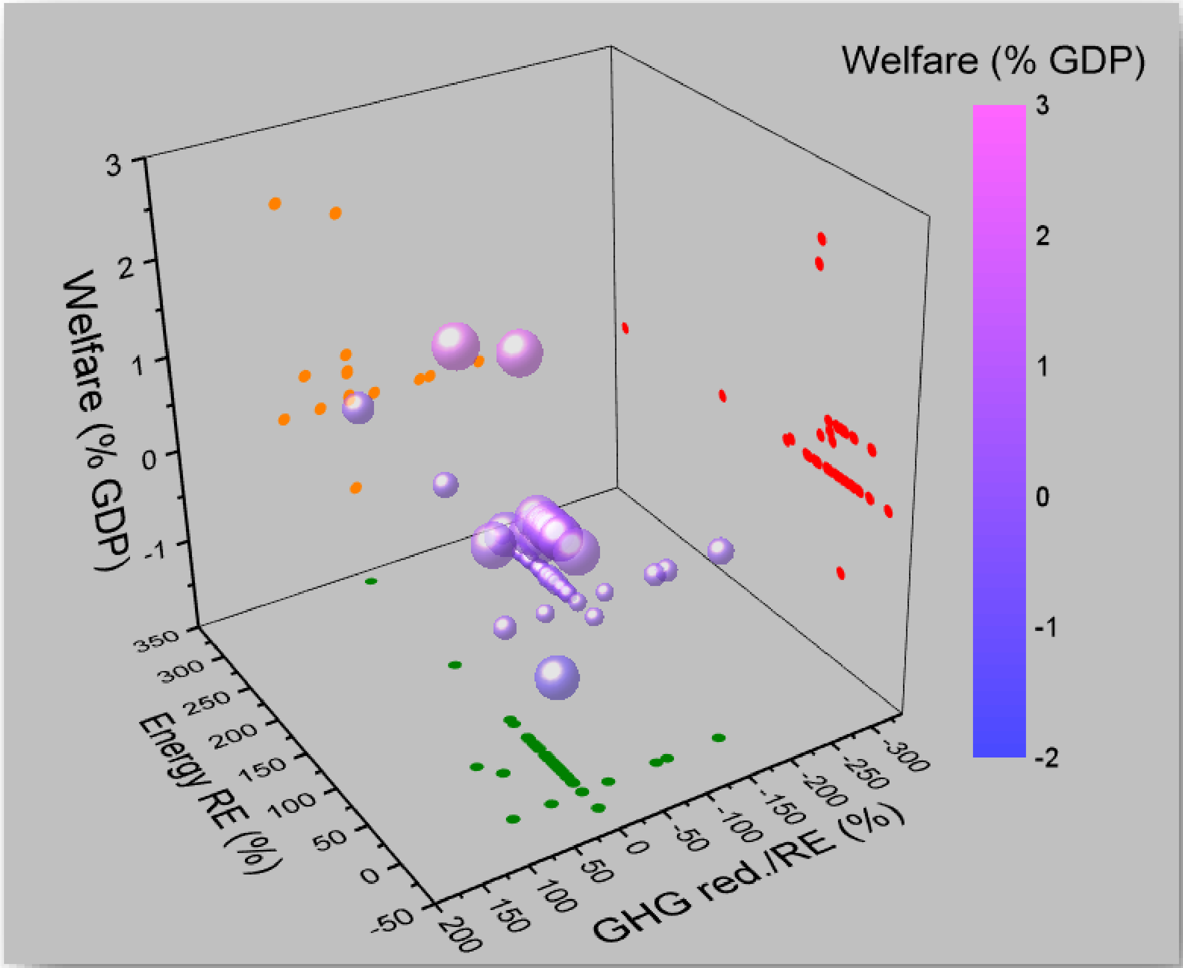
Median 47%

σ 55%

Welfare effects (GDP):

Not computed

Results on all reviewed studies



4.3 Combined insights (2/3): Developed Countries

Studies reviewed: 22

Energy rebound effect:

Ø 50%
Min -22%
Max 78%
σ 23%

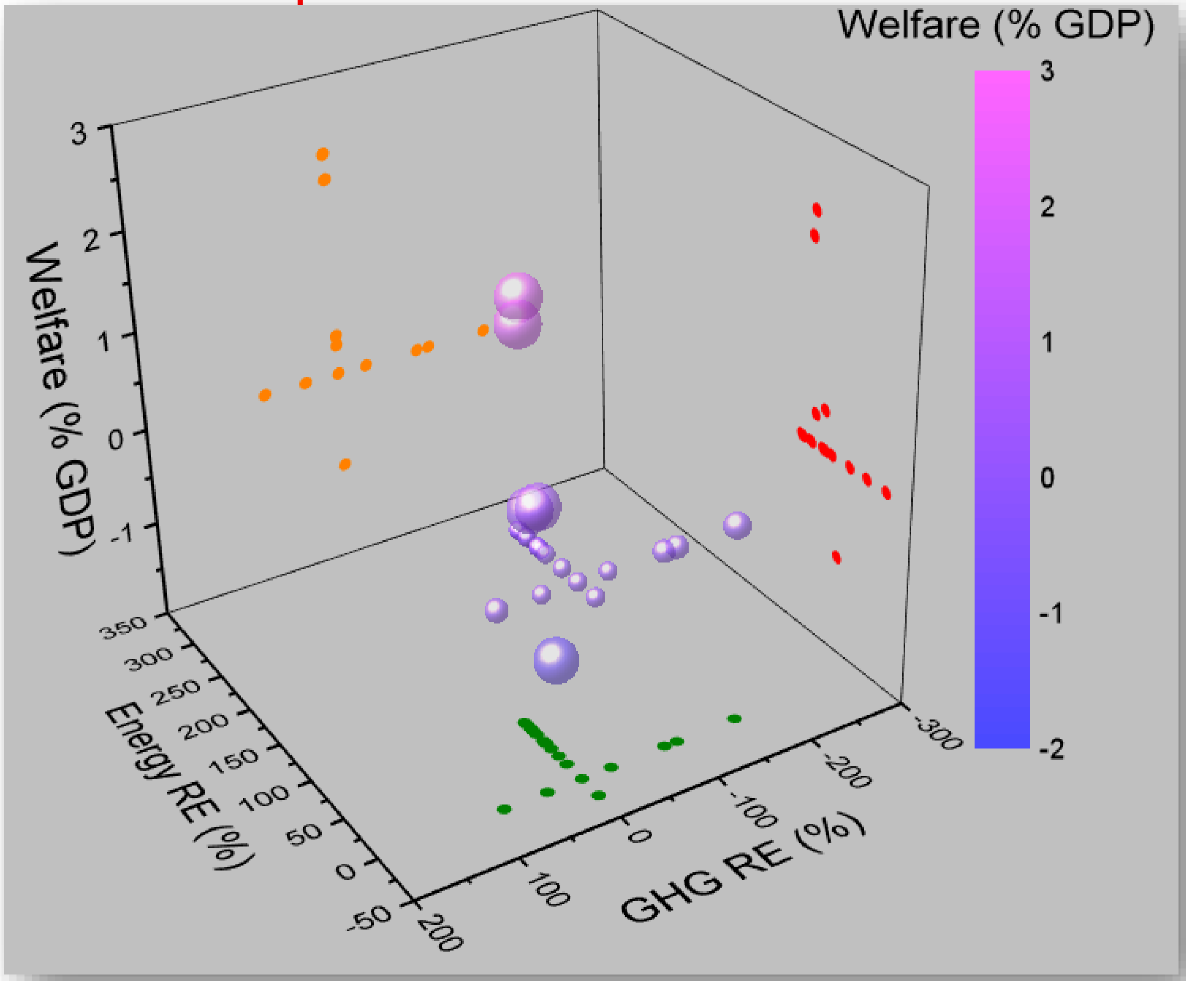
GHG rebound effect:

Not computed

Welfare effects (GDP):

Ø 0.27%
Min -1%
Max 2.25%
σ 0.8%

Results on developed countries



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4.3 Combined insights (3/3): Developing Countries

Studies reviewed: 16

Energy rebound effect:

Ø 67%
Min -0.1%
Max 334%
σ 85%

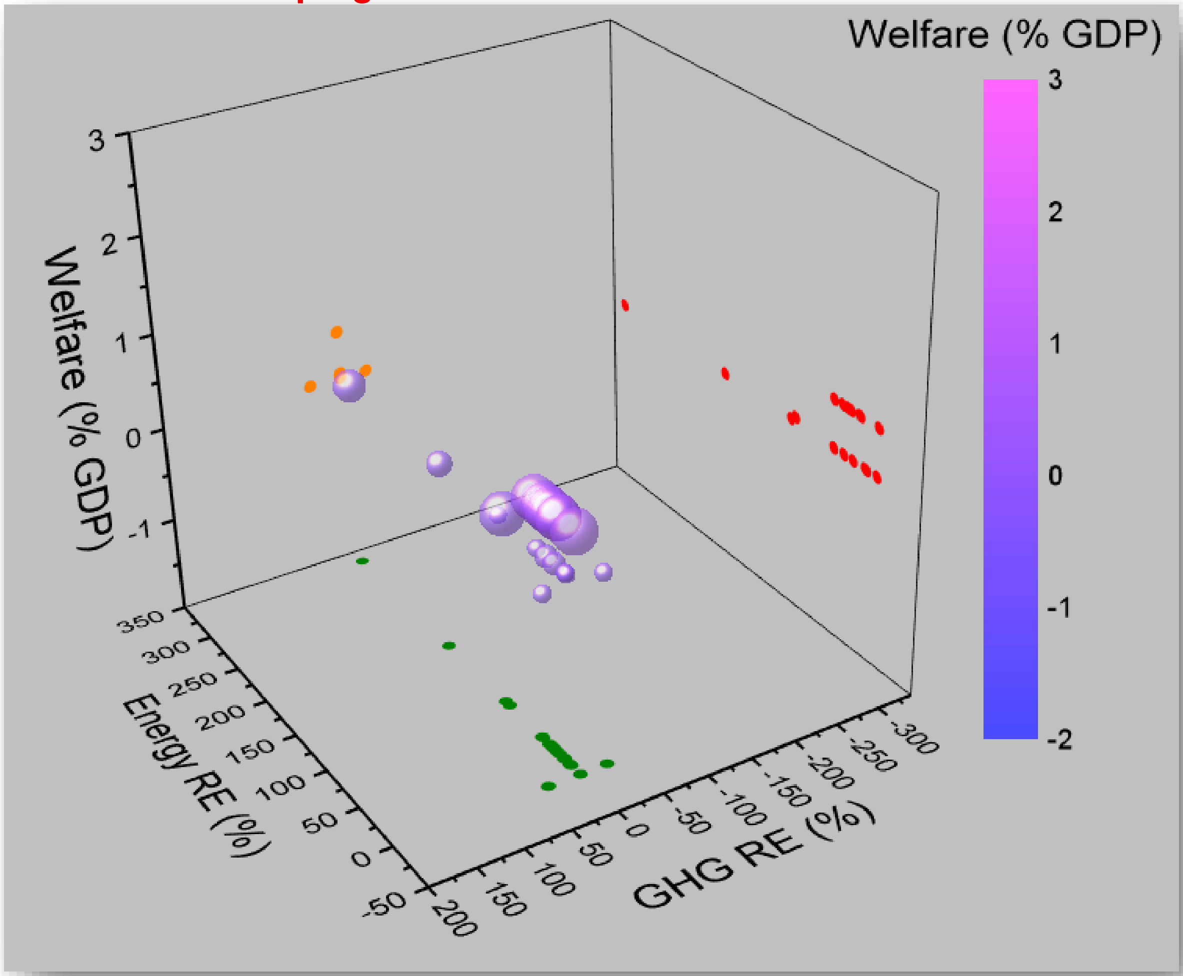
GHG rebound effect:

Not computed

Welfare effects (GDP):

Ø 0.4%
Min 0.05%
Max 0.5%
σ 0.2%

Results on developing countries



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4 Model identification: a trade-off between theory and reality (5/5)

4.3 Combined insights:

Finally, all figures imply that **welfare is a function that depends on GHG reductions and energy savings**. Furthermore, given that the calculation of rebound effects has two components one **expected** (or *ex ante*), and another **real** (or *ex-post*), we suggest that **GHG reductions and energy savings would be better indicators** for policy assessment, due to the possible high variability of the expected component.

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5 Motivations and scope for future research

- Energy efficiency improvements on consumption and production
- Heterogeneity
- Long-run vs. Short-run
- Uncertainty due to expectations and the counterfactual
- Energy efficiency up-front costs
- Imperfect markets, externalities, and imperfect regulations
- Targeting and distributional concerns
- Understanding consumer preferences and changes
- Interactions between energy consumption, GHG emissions reductions, and welfare

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