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Abstract

We develop a stylized general equilibrium model to decompose the rebound effect of energy efficiency improvements into its partial and general equilibrium components. In our theoretical analysis, we identify key drivers of the general equilibrium rebound effect, including a composition channel, an energy price channel, a labor supply channel, and a growth channel. Based on numerical simulations with both the stylized model as well as a large-scale computable general equilibrium model of the global economy, we show that both general and partial equilibrium components of the rebound effect can be substantial. Our benchmark parameterization suggests a total rebound effect due to an exogenous energy efficiency improvement in the US manufacturing sector of 67% with roughly two-thirds occurring through the partial equilibrium rebound channel and the remaining one-third occurring through the general equilibrium rebound channel.

Keywords: energy efficiency, climate change, rebound effect, general equilibrium

JEL codes: C68, D58, Q43, Q55.

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1 Introduction

Improvements in energy efficiency are considered one of the most important and cost-effective pathways for achieving significant cuts in greenhouse gas emissions.[1] However, economists have long recognized that improvements in energy efficiency may lead to increased use of energy services, offsetting a portion of the potential energy savings. The origin of this insight is typically credited to Jevons (1865).[2] More formal analysis of what is now called the *rebound effect* was initiated by Khazzoom (1980) and Brookes (1990), who cast the basic insight of Jevons (1865) into a modern micro-economic framework. These authors showed that in some cases energy efficiency improvements could even *backfire*, resulting in higher overall energy consumption. A large number of more recent contributions, synthesized by Greening et al. (2000) and Sorrell et al. (2007), have provided a taxonomy of the rebound effect along with empirical estimates on its magnitude.

Prior studies divide the rebound effect into three main components: (1) the *direct* rebound effect, whereby consumers substitute energy services for other inputs as the relative price of energy services is reduced due to an energy efficiency improvement; (2) the *respending* rebound effect, where gains in real income resulting from improved energy efficiency are spent on energy services and other goods and services (which themselves require energy to produce); and (3) the *economy-wide* rebound effect, whereby commodity and factor prices throughout the economy return to equilibrium following an improvement in energy efficiency, resulting in changes in energy consumption throughout the economy (Greening et al., 2000; Sorrell et al., 2007). The first two of these are *partial equilibrium* effects, estimated by holding prices throughout the economy fixed (except the price of energy services). The third is a *general equilibrium* effect, which is the net effect of the energy efficiency improvement on energy demand, once all prices in the economy

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[1] For example, a recent analysis by the International Energy Agency (2014) suggests that energy efficiency improvements delivers half of all near-term greenhouse gas reductions.

[2] Jevons was concerned about the exhaustion of British coal supplies, and stated that “It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.” In writing specifically on the steam engine, he stated “Whatever, therefore, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations.” This idea – that improved energy efficiency can lead to increased energy demand – has become known as the “Jevons paradox”.

have returned to equilibrium following the exogenous shock to energy efficiency.[3]

In this paper, we focus on *general equilibrium* rebound effects.[4] While the theoretical analysis of the partial equilibrium rebound effect is well advanced (Chan and Gillingham, 2015; Borenstein, 2015), theoretical insights on general equilibrium rebound effects are less elaborated. Reflecting these different stages in theory-based research, applied economic analysis provides relatively coherent estimates on the magnitude of partial equilibrium rebound effects (Gillingham et al., 2013; Gillingham, 2014; De Borger et al., 2016; Small and Van Dender, 2007), while numerical estimates on the magnitude of general equilibrium rebound effects appear rather scattered. In this context, Greening et al. (2000) state that the size of the general equilibrium rebound effect is "highly uncertain and deserves further study" (p. 391). Borenstein (2015) likewise suggests that general equilibrium rebound effects are ill-understood (p. 11), and Gillingham et al. (2013) say that general equilibrium "rebound effects are hard to pin down" (p. 476).

In this paper, we develop a simple analytical general equilibrium model, in the spirit of Harberger (1962) and Jones (1965), to explore the rebound effect in a general equilibrium setting.[5] We present an analytical solution to the general equilibrium model, which describes the change in overall energy demand following an exogenous improvement to energy efficiency. We decompose the change in energy demand into a partial equilibrium component – which has been the subject of most research so far – and a general equilibrium component, which has received much less scrutiny.

Our model articulates four pathways for the general equilibrium rebound effect to materialize: a composition channel, an energy price channel, a growth channel, and a labor supply channel. General equilibrium rebound via the *composition channel* refers to changes in energy consumption that arise due to structural change in the economy following the exogenous energy efficiency

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[3] A fourth category of rebound effects, sometimes referred to as transformational effects, has been identified. Transformational rebound effects include the potential that changes in energy efficiency have knock-on effects on consumer preferences, social institutions, or other primitive factors (Greening et al., 2000), and are less amenable to quantification.

[4] Greening et al. (2000) refer to general equilibrium rebound effects as *economy-wide* rebound. Saunders (2000) refers to a similar phenomenon as the *macro-economic* rebound effect.

[5] Similar model settings have been used more recently in environmental economics to investigate the incidence of environmental taxation e.g. by Fullerton and Heutel (2007) or Rausch and Schwarz (2016).

improvement. We show that the magnitude of this effect depends on the energy intensity and the size of the sector that receives the energy efficiency improvement as well as the elasticity of substitution between goods in final demand. General equilibrium rebound via the *energy price channel* occurs when an improvement in energy efficiency exerts a downward pressure on energy prices, leading to increased energy consumption that offsets a portion of the original energy savings.[6] We show that the magnitude of this channel depends on the elasticity of supply for energy. General equilibrium rebound via the *growth channel* refers to the idea that an energy efficiency improvement causes an increase in the return on capital, which could stimulate investment and thus increase the steady-state capital stock. In response, the output of the economy increases, causing an increase in energy consumption that offsets a portion of the original energy savings. We show that the magnitude of the rebound effect through the growth channel is determined by the elasticity of substitution between capital and labor as well as the energy intensity of the economy. General equilibrium rebound via the *labor supply channel* can occur because an improvement in energy efficiency will affect the real wage rate. To the extent that consumers adjust labor supply in response to changes in the real wage rate, this will cause a change in labor supplied to productive sectors in the economy, and thus to energy consumption. We show that the magnitude of the rebound effect that occurs through the labor supply channel is directly related to the elasticity of substitution between consumption and leisure. We believe that our paper is the first to offer a taxonomy and systematic decomposition of general equilibrium rebound effects.

As with many economy-wide phenomena, econometrically estimating the effect of the general equilibrium rebound is challenging. To obtain quantitative estimates of the general equilibrium rebound effect, we instead make use of numerical simulations. First, we calibrate our stylized analytic model to US macroeconomic data, to obtain quantitative estimates on the size of the general equilibrium rebound effects that occur through the channels above. These estimates suggest that both partial as well as general equilibrium components of the rebound effect can be substantial. If the elasticity of demand for energy services is low (as is suggested by some recent research, such

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[6] The energy price channel has been identified in prior literature—see for example, Borenstein (2015).

as Gillingham (2014) and Small and Van Dender (2007)), the general equilibrium component of the rebound effect can dominate the partial equilibrium component. Conversely, if the elasticity of demand for energy services is relatively high, the rebound effect is dominated by the partial equilibrium component. Over a range of reasonable parameterizations, three of the channels of the general equilibrium rebound effect identified above—the composition channel, the energy price channel, and the growth channel—can be important contributors, while we find that the labor supply channel does not produce substantial rebound effects.

To check the robustness of our stylized analysis against a more realistic economic setting, we conduct simulations of the rebound effect in a large-scale multi-sector multi-region computable general equilibrium (CGE) model of the global economy. The CGE approach incorporates various real-world features that are absent from the stylized theoretical analysis such as intermediate inputs, multiple primary and secondary energy types, as well as international trade. The CGE results support the previous insights from the stylized analysis: both the partial and general equilibrium components of the rebound effect can be significant. With reference parameter values, our CGE model suggests that the full rebound effect resulting from an exogenous improvement to the energy efficiency of the US manufacturing sector would be 67%, with roughly two-thirds of this amount occurring through the partial equilibrium channel and one-third through the general equilibrium channel. Decomposing the general equilibrium channel, our model suggests that approximately half of the general equilibrium rebound occurs via the composition channel, and one-quarter through each of the growth and energy price channels. We do not find a substantial role for the labor supply channel in general equilibrium rebound.

A number of other papers have studied rebound effects in general equilibrium, either using theoretical analysis or building on computable general equilibrium simulations. On theoretical grounds, our analysis extends the one-sector general equilibrium model by Saunders (2000) and Wei (2007, 2010) and the multi-sector approach by Lemoine (2016). The one-sector approaches of Saunders (2000) and Wei (2007, 2010) emphasize the investment and growth effects of energy efficiency improvements, and note that improvements in energy efficiency can spur investment, leading to higher growth and energy consumption. Because they build on single-sector models, these approaches ignore the potential impacts of energy efficiency improvements on inter-sectoral output and energy consumption. These papers also do not decompose the drivers of general equilibrium rebound. Lemoine (2016) builds a static multi-sector model, similar to the one presented here, but focuses on what we call the composition channel. We articulate additional channels through which general equilibrium rebound can occur, and complement the theoretical analysis with quantitative estimates using a computable general equilibrium model (CGE).

As to CGE estimates for general equilibrium rebound effects, Grepperud and Rasmussen (2004) apply the MSG-6 model to Norway and investigate exogenous energy efficiency improvements across six sectors individually (one-by-one). The authors report the sectoral rebound effect, rather than the overall rebound effect, i.e., they do not report the overall change in energy consumption following the exogenous shock. For the six different sectors, they identify opposing impacts (i.e., in some sectors, energy efficiency increases sectoral energy demand, while the opposite occurs in other cases). In a series of papers using the ENVI model for the UK and Scotland, researchers report the overall change in energy consumption following an exogenous improvement in the energy efficiency for one sector of the economy (Allan et al., 2006; Hanley et al., 2006, 2009; Turner and Hanley, 2011). Energy efficiency improvements in a sector lead to increases in economy-wide energy consumption, hence pointing to a rebound effect which is more than offsetting the initial energy efficiency improvement. The ENVI work builds on extensive sensitivity analysis, but no formal decomposition is undertaken to elucidate on the mechanisms that lead to rebound. Lecca et al. (2014) evaluate changes in energy efficiency of the household sector using a CGE model for the UK. They offer some decomposition, by freezing prices to simulate partial equilibrium rebound, and allowing prices to move, to simulate general equilibrium rebound. In their analysis, the rebound effect turns out to be slightly less in general equilibrium than in partial equilibrium (i.e., the general equilibrium component of the rebound effect is negative). The rebound effect in total amounts to roughly 50-60% of the initial energy efficiency improvement. Koesler et al. (2016) employ a multi-sector multi-region CGE model of the world economy to simulate a costless 10%

improvement in energy efficiency across German production sectors. Adding up changes in energy use across all regions and sectors of their model, they find that the total rebound is about 50%.

Against the existing literature, our analysis stands out for the rigorous combination of theoretical and computable general equilibrium analysis. The theoretical section provides an analytical framework for decomposing the rebound effect into various components. Finally, we apply a large-scale CGE model calibrated to empirical data to substantiate the findings from our stylized analysis and quantify the rebound effect for the US, China, and the EU economies.

The remainder of the paper is organized as follows. In section 2 we develop a simple model to derive closed-form solutions for the various components adding up to the total rebound effect; we furthermore parametrize the simple analytical model with macroeconomic data for the US economy to obtain rough estimates on the magnitude of the rebound effect associated with exogenous energy efficiency improvements. In section 3 we adopt a standard CGE model to estimate the magnitude of the general equilibrium rebound effect in a multi-country multi-region setting. In section 4 we conclude.

2 Theoretical considerations

We first develop a simple static one-sector closed economy general equilibrium model with fixed labor supply and constant energy prices. We use the model to solve for the change in economy-wide energy consumption caused by an exogenous improvement in energy efficiency. In this formulation, there are no general equilibrium rebound effects, but introducing the simple model is useful for pedagogic purposes. We then successively introduce four extensions to the simple model that give rise to general equilibrium rebound effects: (1) the *composition channel*: we introduce multiple sectors, such that an energy efficiency improvement in one sector of the economy can cause a structural change in the composition of the economy that affects energy consumption, (2) the *energy price channel*: we introduce declining returns to scale in energy production, such that an energy efficiency improvement can cause a reduction in energy prices, which stimulates energy consumption, (3) the *growth channel*: we introduce a steady-state capital stock closure, such that an exogenous energy efficiency improvement can affect the steady-state capital stock and thus the consumption of energy via its effect on total output, and (4) the *labor supply channel*: we introduce a leisure-consumption choice in the consumer utility function, such that labor supply is endogenous, and the exogenous improvement in energy efficiency can affect energy consumption by its effect on total output. In each case, we solve analytically for the change in energy consumption that occurs due to an exogenous change in the energy efficiency of the economy, and calculate the rebound effect as the proportion of the initial energy savings that are gained or lost due to economic responses to the exogenous shock. Finally, we conduct numerical simulations with the stylized analytical model using just a few macroeconomic figures for the US economy.

2.1 Benchmark analytical model

We begin with a one-sector closed economy static general equilibrium model with fixed labor supply and fixed energy price to illustrate our approach, set notation, and to provide a benchmark for comparison with the subsequent model extensions. This model exhibits partial equilibrium rebound, but not general equilibrium rebound, since there is no mechanism in the model through which the latter can occur. The extensions to the model—which are the focus of the paper—elucidate four mechanisms through which general equilibrium rebound can occur.

Our benchmark stylized analytical model of a closed economy features one sector, which we denote X. It produces output by combining two inputs: value-added V_X[7] and energy services S_X, where the substitution elasticity between the two inputs is given by σ_X. Energy service inputs are derived from energy E_X, in the form $S_X = A_X E_X$, where A_X is the efficiency with which energy inputs to sector X are translated into energy services.[8] For example, if the energy service is lighting, and the energy input is electricity, the parameter A_X refers to the efficiency with which

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[7] The value-added aggregate refers to some combination of capital and labor. While we articulate the components of the value-added aggregate at a later point, here, we are agnostic as to the composition of this aggregate.

[8] This is a standard set-up in the rebound effect literature. See, for example, Chan and Gillingham (2015) or Allan et al. (2006).

electricity is converted into lighting services. Energy is produced with a linear technology using the value-added input, such that $E = V_E$. This formulation ensures that the price of energy is constant relative to the price of the value-added factor, which eliminates the energy price mechanism in determining the rebound effect.[9] The representative consumer has a fixed endowment of the productive factor, $\bar{V}$ (the overbar indicates a fixed quantity), which it uses to finance consumption of the produced good, X. The endowment of $\bar{V}$ is used by sectors X and E to produce the consumption good and energy, respectively. In this model and the following extensions, we assume a perfectly competitive economy in which all markets clear without frictions. Appendix A contains an algebraic description of the model, which we present in linearized form similarly to Harberger (1962), Jones (1965), or Fullerton and Heutel (2007) to obtain a closed-form solution to the model.

2.2 Derivation of rebound effects

Our analytical experiment involves an exogenous and costless improvement in the efficiency of producing energy services to sector X, which we model as an increase in A_X.[10] Continuing the example above, one such improvement might be an exogenous innovation in lightbulbs (such as the introduction of LED lightbulbs), which reduce the electricity required to produce a unit of lighting services. Our model does not consider the source of the improvement in energy efficiency, but rather treats it as costless and exogenous, and studies the consequences of this improvement (this set-up follows the extensive literature on the rebound effect, for example, Chan and Gillingham (2015) or Allan et al. (2006)).

We begin with the notion of what is usually termed as the "engineering" energy savings resulting from energy efficiency improvements. These savings denote the reduction in energy demand due to the efficiency improvement, without any behavioral response. We refer to the "engineering" energy savings as the common benchmark for potential energy savings and estimate what frac-

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[9] The model also imposes the assumption that energy is only consumed as an intermediate input (i.e., energy is not consumed directly by the consumer). This assumption is relaxed in the more complete model introduced later in the paper.

[10] Borenstein (2015) models costly improvements in energy efficiency and shows that this reduces the rebound effect. We follow the bulk of the literature in estimating the response to a costless exogenous energy efficiency improvement.

tion of this "engineering" energy savings is eroded by behavioural responses, i.e., rebound effects. The latter are distinguished into (i) the partial equilibrium rebound effect that arises through the substitution channel (this is what is typically known as the direct rebound effect), (ii) the partial equilibrium rebound effect that arises through the income channel (this is sometimes referred to as respending rebound), and (iii) the general equilibrium rebound effect which captures all the residual energy demand effects when all prices adjust towards general equilibrium across all markets. Partial equilibrium rebound effects are estimated by holding all prices fixed except for the price of the energy service that is affected directly from the exogenous energy efficiency improvement. The full rebound effect is thus the sum of the partial equilibrium components and the general equilibrium component.

For our benchmark model, the change in energy consumption following an exogenous improvement in the energy efficiency of sector X is given by:

$$\frac{\hat{E}}{\hat{A}_X} = \underbrace{-1}_{\text{Engineering savings}} + \underbrace{\theta_{XV}\sigma_X}_{\text{Partial equilibrium substitution channel}} + \underbrace{\alpha_E}_{\text{Partial equilibrium income channel}}, \qquad (1)$$

where θ_{XV} is the cost share of the value-added input in X production and α_E is the overall energy intensity of the economy.[11] The change in overall energy consumption following the exogenous energy efficiency improvement is separated into three terms in equation (1). Ignoring any behavioural response, each unit of energy efficiency improvement yields one unit of energy savings—this is the first term in equation (1).[12]

Improvements in energy efficiency reduce the real price of the energy service. This reduction in price stimulates consumption of the energy service, as firms move along their compensated energy service demand curve. This increased consumption of energy services offsets a portion of the original energy savings. Following the literature, we refer to increases in energy consumption that occur through this channel as the partial equilibrium substitution channel (this channel is

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[11] Note that in this simple benchmark model, $\theta_{XV} = 1 - \alpha_E$, although this will not hold in the more complex models we introduce in the following sections. See Appendix A for complete notation and derivation.

[12] We derive the engineering measure of energy savings from the model in Appendix A by solving for the change in energy consumption following the change in A_X holding all prices in the model fixed.

sometimes also referred to as direct rebound). We calculate the magnitude of change in energy demand due to the partial equilibrium substitution channel by solving the model in Appendix A while holding all prices except the real price of energy services (p_{SX}) fixed, and while holding real income fixed. The increase in energy consumption due to the partial equilibrium substitution effect is given by $\theta_{XV}\sigma_X$, which is simply the compensated elasticity of demand for energy services by sector X. If the elasticity of demand is small, the change in energy consumption that occurs through the partial equilibrium substitution channel is likewise small. If the elasticity of demand for energy services is greater than unity, the increase in energy consumption that occurs through the partial equilibrium substitution channel more than offsets the original engineering energy savings, resulting in partial equilibrium "backfire". A substantial literature estimates partial equilibrium substitution effects empirically, and finds that between 10 and 50% of engineering energy savings might be offset through this channel (Gillingham et al., 2013; Borenstein, 2015).

Improvements in energy efficiency also increase real income, which relaxes the consumer budget constraint and allows additional consumption. To the extent that this additional consumption requires energy to produce, a portion of the original energy savings will be offset. We refer to additional consumption that occurs because of changes in real income following the exogenous improvement in energy efficiency as the partial equilibrium income channel. Changes in energy consumption due to the partial equilibrium income channel are calculated by solving for the model equilibrium while holding all prices fixed except the real price of energy services, following an exogenous improvement in energy efficiency.[13] Changes in energy consumption via the partial equilibrium income channel are given by α_E, which is the overall energy intensity of the economy. This is intuitive, and indeed has been pointed out by others (e.g., Greening et al., 2000; Borenstein, 2015, and others). Assuming no changes in relative prices, increases in real income will be spent on all goods in the same proportion, and with the same energy intensity, as benchmark expenditures, which is given by α_E in our model. Importantly, this indicates that changes in energy consumption due to the partial equilibrium income channel are likely to be relatively small in

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[13] This approach recovers the sum of partial equilibrium income and substitution effects. To obtain the partial equilibrium income effect, we subtract the partial equilibrium substitution effect, derived above.

magnitude. For example, the energy intensity of the US economy is about 3% (i.e., energy makes up 3% of all intermediate goods expenditures), so increases in energy consumption due to the partial equilibrium income channel in the US only offset 3% of original energy savings following an exogenous improvement in efficiency.[14]

Following the extensive literature on this topic, we define the rebound effect (R) as the fraction of the engineering savings that are offset by behavioural responses:

$$R = \underbrace{\theta_{XV}\sigma_X}_{\text{Partial equilibrium substitution channel}} + \underbrace{\alpha_E}_{\text{Partial equilibrium income channel}} . \tag{2}$$

As stated earlier, in this simple model there is no general equilibrium rebound, since there is no mechanism through which this could occur. Having now introduced the benchmark model and notation, we turn to four model extensions that generate the possibility for general equilibrium rebound, and solve for the magnitude of this effect.

2.3 General equilibrium rebound: Composition channel

In this section, we introduce another economic sector, Y. Sector Y is defined similarly as sector X—requiring inputs of both the value-added input as well as energy services. Since there are now two goods in the economy, we also define consumer preferences over the two goods, using the elasticity of substitution σ_U. The full model is described in Appendix B. As above, we impose a small improvement in the energy efficiency of sector X, and solve the model for the change in energy consumption that results. We obtain the following expression for the rebound effect, which incorporates both partial equilibrium and general equilibrium components:

$$R = \underbrace{\theta_{XV}\sigma_X}_{\text{Partial equilibrium substitution rebound}} + \underbrace{\alpha_E}_{\text{Partial equilibrium income rebound}} + \underbrace{\sigma_U \psi(\alpha_E - \theta_{YS})}_{\text{General equilibrium rebound}} , \tag{3}$$

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[14] See the following section and Appendix F for data sources and calculations. Note that the model in this section ignores energy consumption in final demand, so the true energy intensity including this amount is slightly higher. The model presented later in the paper includes energy consumption in final demand.

where σ_U is the consumer's elasticity of substitution between goods X and Y, θ_{YS} is the energy intensity of sector Y, and ψ denotes the total benchmark output of sector Y relative to sector X.

The partial equilibrium components of the rebound effect are identical to those calculated in the benchmark model. The general equilibrium component of the rebound effect in this model captures substitution from Y to X as the energy efficiency of X improves. Because the price of X always declines as the exogenous energy efficiency of energy services used by X improves, there is always substitution from Y to X in response to an exogenous improvement in the energy efficiency of X. The effect of this substitution on energy consumption depends on the relative energy intensity of sectors X and Y. If sector Y is more energy intensive than the economy as a whole, then $\theta_{YS} > \alpha_E$ and the substitution effect is negative, reinforcing the original energy savings. If sector Y is less energy intensive than the rest of the economy, then the substitution effect is positive, offsetting some of the original savings. The substitution effect becomes more important if there is a large difference in energy intensity between sectors of the economy (i.e., if $(\alpha_E - \theta_{YS})$ is large in absolute value). Notably, if sectors have identical energy intensity in the benchmark (i.e., homogeneous sectors), the general equilibrium rebound effect through the composition channel is zero. The general equilibrium component of the rebound effect is also larger when the elasticity of substitution between sectors X and Y is larger, since in this case the reduction in price of X leads to a larger substitution from Y to X. Furthermore, the general equilibrium rebound effect is larger when sector Y is relatively larger than sector X (i.e., when ψ is large). In this case, a percentage increase in the output of Y has a larger impact on overall energy consumption.

2.4 General equilibrium rebound: Energy price channel

In the benchmark model, energy was produced with a linear technology, such that the price of energy was fixed relative to the price of the value-added input. We can relax the assumption of fully elastic energy supply by introducing a fixed factor in energy supply which generates an upward-sloping energy supply curve (see Fullerton and Heutel (2007) for a similar approach). Energy production now requires both value-added and energy resources (Z), the latter being in fixed supply. The full model is provided in Appendix C. Solving the model generates the following expression for the rebound effect:

$$R = \frac{\frac{\alpha_E}{1-\alpha_E}\frac{1}{\theta_{EV}} + \sigma_X \left(\frac{1}{\eta} + 1\right)}{1 + \frac{\alpha_E}{1-\alpha_E}\frac{1}{\theta_{EV}} + \frac{1}{\eta}\sigma_X}, \tag{4}$$

where θ_{EV} is the cost share of the value-added input in energy production, and $\eta = \frac{\hat{E}}{\hat{p}_E}$ is the elasticity of supply of energy.

An exogenous improvement in the efficiency of energy services now causes an additional change in energy consumption relative to the benchmark model. In particular, if the efficiency improvement causes a reduction in energy demand, then this puts downward pressure on energy prices, which stimulates additional energy demand. A portion of the original energy savings is thus offset through the energy prices channel. As the elasticity of energy supply η is reduced, the rebound effect is increased. As the elasticity of supply of energy approaches zero, the rebound effect approaches 1 (complete erosion of energy savings). As the elasticity of supply of energy approaches infinity, the rebound effect converges on the expression (2).[15]

2.5 General equilibrium rebound: Growth channel

The formulation of our model is static, whereas a number of authors have considered the potential that exogenous improvements in energy efficiency could affect investment and capital stock, and thus have an effect on energy consumption through changes in the growth rate (Saunders, 2000; Wei, 2007). We therefore modify our simple static model to provide insight on the impacts of an exogenous energy efficiency improvement on the steady-state capital stock, and thus the general equilibrium rebound effect that may occur through the growth channel. In order to capture dynamics in our static model we implement a standard steady-state constraint (see Rutherford and Paltsev (1999)). In this approach, the steady-state capital stock is determined by the level of investment. Investment is endogenous and responds to the return of capital relative to the price of the invest-

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[15] As a special case, equation (4) nests the simple model of equation (2) by setting $\theta_{EV} = 1$ and $\eta = \infty$.

ment good. Implementing the steady-state formulation requires several changes to the model. First, we introduce an investment good, and allow the capital stock to be endogenous, rather than fixed. In our one-sector model, the investment good is identical to the consumption good, X. Second, we separate the value-added aggregate into capital and labor, to allow us to explicitly consider the steady-state capital stock. Third, we impose the steady-state condition that changes in the price of the investment good must be identical to changes in the return on capital. We ensure that this condition is met by allowing the capital stock to be endogenous. We describe the full model and solution in Appendix D. As before, we decompose the change in energy consumption into partial and general equilibrium components:

$$R = \underbrace{\theta_{XV}\sigma_X}_{\text{Partial equilibrium substitution rebound}} + \underbrace{\alpha_E}_{\text{Partial equilibrium income rebound}} + \underbrace{\frac{\theta_{VK}}{1-\theta_{VK}}\alpha_E\sigma_V}_{\text{General equilibrium rebound}} , \quad (5)$$

where θ_{VK} is the share of capital in value-added, and σ_V is the elasticity of substitution between capital and labor.

The partial equilibrium rebound terms are the same as in prior models. The general equilibrium rebound term is positive, such that rebound effect that occurs through the growth channel offsets a portion of the original energy savings. This occurs because the exogenous energy efficiency improvement raises the return on capital relative to the price of the investment good. To return to steady state, investment and thus the steady-state capital stock increases, which increases steady state output. The increase in output causes an increase in energy consumption, which offsets a portion of the initial energy savings. We can use a simple back-of-the-envelope calculation to obtain an order-of-magnitude estimate for the size of the general equilibrium rebound that occurs through the growth channel. For example, if capital is 40% of value-added ($\theta_{VK} = 0.4$), the energy intensity of the economy is $\alpha_E = 0.03$, and the elasticity of substitution between capital and labor is 1, the general equilibrium rebound that occurs through the growth channel is 0.02. In other words, changes to the steady-state capital stock offset 2% of the original energy savings for our illustrative parameterization.

2.6 General equilibrium rebound: Labour supply channel

Our benchmark model treats labor as a fixed endowment of the consumer, whose supply is invariant to changes in the real wage. Here, we augment our model by treating the labor supply as endogenous. As a result, to the extent that the exogenous improvement in energy efficiency impacts the real wage rate, the consumer responds by adjusting labor supply. The change in labor supplied affects the output of the economy, which in turn affects overall energy consumption. We implement the endogenous labor supply with several changes to our benchmark model. First, as in Section 2.5, we disaggregate the value-added aggregate into its constituents capital and labor. We treat the capital stock as fixed. The consumer is now endowed with an exogenous time budget, which is optimally allocated between consumption and leisure to maximize utility. We describe the full model in Appendix E. The solution to the model gives the following result for the rebound effect following an exogenous energy efficiency improvement in sector X:

$$R = \frac{\theta_{XV}\sigma_X + \sigma_Z\theta_{XS} + \delta(\sigma_X(1-\alpha_E)+\alpha_E)}{1+\delta}, \tag{6}$$

where σ_Z is the elasticity of substitution between consumption and leisure, and δ is the elasticity of consumption with respect to the endowment (income). Note that in the model without leisure, $\delta = 1$, and we obtain the same expression for R as in the simple model above.

Introducing endogenous labor supply has an ambiguous impact on the rebound effect, that depends especially on the elasticity of substitution between leisure and consumption, σ_Z. In particular, for values of σ_Z greater than unity, the improvement in energy efficiency reduces the price of the consumption good, and the consumer substitutes into increased consumption of this good and away from leisure, which increases labor supply, economic output, and energy consumption. Values of σ_Z greater than unity therefore imply that the labor supply channel exacerbates the rebound effect and that the general equilibrium component of the rebound effect via the labor supply channel is positive. Values of σ_Z less than unity have the opposite effect, whereby the labor supply channel of the general equilibrium rebound effect is negative, such that full rebound is smaller than partial equilibrium rebound.

The elasticity of substiution between leisure and consumption is directly related to the labor supply elasticity.[16] A substantial amount of evidence suggests that the labor supply elasticity is low across the economy as a whole, such that σ_Z is likely below unity; thus including the labor supply channel likely reduces the overall rebound effect.

2.7 Stylized numerical simulation

We parametrize the simple analytical model to get a first idea on the order of magnitude for the various rebound effects identified above. We do this for the US as a large energy consuming country using macroeconomic figures from the Bureau of Economic Analysis for the year 2010.[17] For our multi-sector parametrization we refer to X as a composite sector composed of agriculture, mining (except oil and gas), utilities, and energy-intensive manufacturing, E as the composite of coal, oil, and gas mining as well as petroleum refining, and Y as composite production and service sector for the rest of the economy.[18] Energy goods are represented as a composite of refined petroleum products, gas, and coal. Table 1 provides the cost and demand share parameters derived from this source. The X sector uses 12 percent of total capital and 29 percent of total energy, such that it is more energy intensive than the Y sector. As the table shows, the cost share of energy services in the X sector is 7 percent, compared to 2.5 percent for the Y sector.[19]

We quantify the rebound effect for a small (1%) improvement in the energy efficiency of the X sector for alternative assumptions on key elasticities, i.e., the elasticity of substitution σ_X between value-added and energy in the X sector and the elasticity of substitution σ_U between X and Y in final consumption. The reference values for these elasticities are set to 0.5 and 1, respectively, in

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[16] In a similar general equilibrium setting, Ballard (2000) derives the substitution elasticity between leisure and consumption as $\sigma_Z = \frac{\varepsilon^*}{\frac{\theta_{TZ}}{\theta_{TL}}(1-\varepsilon^*+\varepsilon)}$, where ε and ε^* are the uncompenstated and compenstated labor supply elasticities, respectively. Assuming $\theta_{TL} = \theta_{TZ} = 0.5$, ε^*=0.3, and ε=0.05 (similar to Ballard (2000)) gives σ_Z=0.4.

[17] Appendix F describes the data source and calculations.

[18] See Appendix F; for the single sector model, we merge sectors X and Y together.

[19] In our stylized model, we only consider the consumption of energy as an intermediate input, and do not consider energy consumption in final demand. We do account for energy consumed directly by consumers in the more comprehensive CGE model that follows later in the paper.

Parameter	Description	Value
α_X	Share of capital by X sector	0.115
α_Y	Share of capital by Y sector	0.854
α_E	Share of capital by E sector	0.030
θ_{XS}	Cost share of energy services in X production	0.071
θ_{YS}	Cost share of energy services in Y production	0.025

Table 1: US parameter values for stylized numerical analysis (Source: 2010 US BEA. Values may not add up to 100% due to rounding.)

line with the empirical literature. For example Okagawa and Ban (2008) econometrically estimate the elasticity of substitution between a capital-labor aggregate and energy, and find values centered around 0.5.

Based on these values, we can use equations (2), (3), (4), (5), and (6) to estimate the rebound effect associated with an exogenous improvement in the energy efficiency of the X sector. We find that the partial equilibrium rebound effect via the substitution channel in the one-sector model is $\theta_{XK}\sigma_X = 48.5\%$, which corresponds to the compensated elasticity of energy service demand in the X sector. The partial equilibrium rebound via the income channel is $\alpha_E = 3\%$, which corresponds to the energy intensity of the economy as a whole (again, ignoring for the time being energy used in final demand). The partial equilibrium rebound effect is thus 51.5%, assuming an elasticity of substitution between energy services and value-added of 0.5. We break down general equilibrium rebound effects into four components. First, the composition channel reflects substitution from Y to X as the energy efficiency of X exogenously improves. The magnitude of this rebound effect is $\sigma_U \psi(\alpha_E - \theta_{YS}) = 1\%$. Second, the growth channel reflects an increase in the steady-state capital stock and thus level of output resulting from increases in the productivity of capital caused by exogenous improvements in energy efficiency. The magnitude of this rebound effect is $\frac{\theta_{VK}}{1-\theta_{VK}}\alpha_E\sigma_V = 2\%$ given our parameterization. Third, the energy price channel reflects offsetting increases in energy consumption due to reduction in the price of energy caused by the energy efficiency improvement. The magnitude of this effect is about 10% for an energy supply elasticity of 2 and about 23% for an energy supply elasticity of 0.5. Fourth, the labor suply channel reflects an endogenous change in labor supply induced by a change in the real wage rate, which in turn is due to the exogenous energy efficiency improvement. Assuming that half of benchmark time is spent on leisure and that the elasticity of substitution between goods and leisure is 0.4 (see footnote 16), we obtain -0.6% for the general equilibrium component of the rebound effect that occurs via the labor supply channel. In total, the general equilibrium component of the rebound effect for our base parameterization is between 13 and 26%, and the sum of partial and general equilibrium components is 64.5% to 77.5%. The general equilibrium component of rebound is thus smaller than the partial equilibrium component at our base parameter values, but still substantial.

Figure 1 provides a graphical illustration on how the various rebound effects change as we alter our key elasticities from their reference values. In the left-hand panel, we depict the rebound effects for different values of σ_X (while keeping σ_U at the reference value). As is well known, the partial equilibrium rebound effect via the substitution channel depends on the elasticity of demand for energy services, which is closely related to the elasticity of substitution between value added and energy services (see Equation (2)). For an elasticity of demand larger than one, there is partial equilibrium backfire, where the rebound effect exceeds 100%. Empirical estimates of the elasticity of demand for energy services suggest that this elasticity is typically well below one, such that the partial equilibrium rebound effect via the substitution channel is likely to be well below 100% (Sorrell et al., 2009; Gillingham et al., 2013).

The partial equilibrium rebound effect that operates through the income channel—referred to also as 'respending rebound'—captures the embodied energy of goods that are purchased as a result of the income gains emerging from exogenous energy efficiency improvements. As discussed above, for the US economy as a whole, energy expenditures represent about 3% of total expenditures, so the partial equilibrium rebound effect that operates through the income channel takes on this value. Recall that the partial equilibrium rebound effect through the income channel remains constant as the value of σ_X (or likewise σ_U) changes (see equation (2)). The solid black line in Figure 1 includes both components of the partial equilibrium effect (the substitution and income components).

The full rebound effect includes both the partial and general equilibrium components. We calculate the general equilibrium portion of the rebound effect by successively adding the composition channel, the growth channel, the labor supply channel, and the energy price channel to our benchmark model, to illustrate the composition of the total rebound effect.[20] For the parameters selected, the composition channel and growth channel add only a small amount to the partial equilibrium rebound effect, while the labor supply channel slightly reduces overall rebound. The energy price channel is more important, particularly if the elasticity of energy supply is low or the elasticity of substitution in sector X is low. In this case, the general equilibrium component of the rebound effect can even be larger than the partial equilibrium component.[21] Including imperfectly elastic fuel supply increases the overall rebound effect over the empirically relevant parameter range.

The right-hand panel of Figure 1 shows how the rebound effects change as we alter the elasticity of substitution σ_U that governs the household substitution between X and Y. High values for σ_U mean that the household can more easily switch consumption into the X sector following the improvement in energy efficiency of that sector (which reduces its relative price). With the US data, the X sector is more energy intensive than the Y sector, so this switch erodes a portion of the energy savings. In the case where good X is traded internationally, such that the elasticity of demand for good X is relatively high, the composition channel can be a significant contributor to the overall rebound effect. In the large-scale model in the following section, we explore this more rigorously.

3 Computable general equilibrium analysis

The previous section provided a theoretical framework for the analysis of energy rebound effects based on a simple two-sector general equilibrium model of a closed economy. While the stylized analysis is useful for disentangling price and income effects that drive the rebound effect, it abstracts from various potentially important real-world complexities, such as intermediate inputs,

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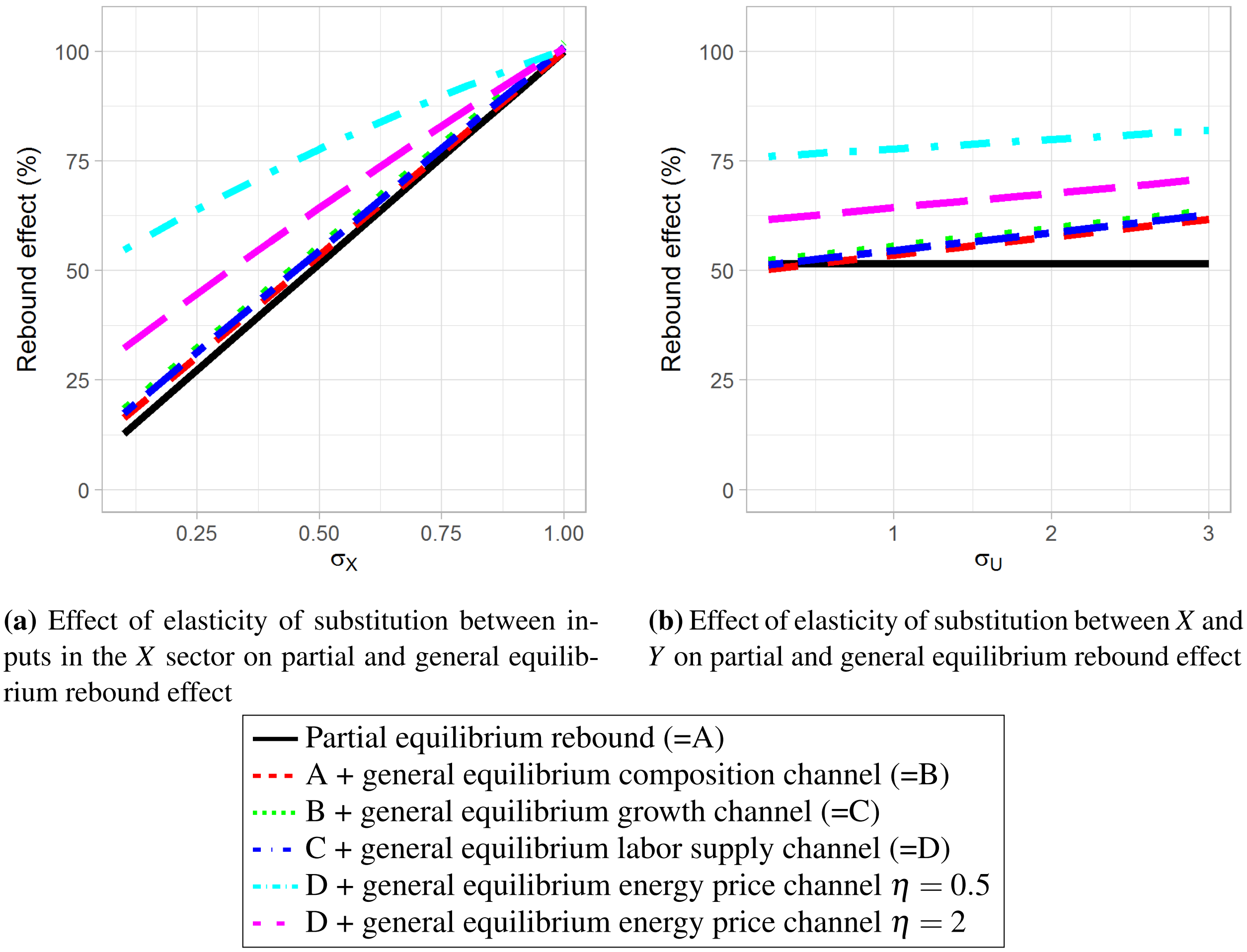
[20] Note that because the simple model we derive is linear, the results are invariant to the order in which the decomposition is carried out (Harrison et al., 2000).

[21] In the limit, as $\eta \to 0$, rebound becomes complete (100%).



(a) Effect of elasticity of substitution between inputs in the X sector on partial and general equilibrium rebound effect

(b) Effect of elasticity of substitution between X and Y on partial and general equilibrium rebound effect

Figure 1: Numerical estimates of the rebound effect using benchmark cost shares from the 2010 BEA, corresponding to an exogenous improvement in the energy efficiency of the energy-intensive (X) sector. The left hand panel (a) displays the rebound effect for different values of σ_X and uses $\sigma_U = 1$. The right hand panel (b) displays the rebound effect for different values of σ_U and uses $\sigma_X = 0.5$. The partial equilibrium rebound includes both the substitution and income effects.

international trade, more complex production functions, additional factors of production, and multiple energy carriers. In order to draw more viable policy conclusions, we complement our stylized analysis with applied analysis based on numerical simulations with a large-scale CGE model. Like our stylized analysis, the CGE approach builds rigorously on microeconomic general equilibrium theory. However, it accommodates the treatment of more complex (flexible) functional forms to represent production technologies and consumption preferences across many commodities and factors based on empirical data.

CGE models combine data from input-output tables with assumptions about market structure and elasticities that govern how responsive supply and demand are to price changes. They are well established in applied economic analysis to assess the outcome of how the economy adjusts to policy interventions.

Below we first provide a short non-technical summary of our standard multi-sector multi-region CGE model used for the quantitative assessment of the energy rebound. Next, we briefly refer to the data for model parametrization. Finally, we discuss the results from numerical simulations on the magnitude of the energy rebound effect.

3.1 Non-technical CGE model summary

We start from a generic static multi-sector multi-region computable general equilibrium (CGE) model of global trade (Lanz and Rutherford, 2016) which we extend towards a more refined representation of energy demand and supply (Böhringer et al., 2016).[22]

Producers employ primary factors and intermediate inputs in least cost combinations subject to technological constraints, while consumers with given preferences maximize their well-being subject to budget constraints. Output and factor prices are fully flexible on perfectly competitive markets. Technologies and preferences are described through nested constant-elasticity-of-substitution (CES) functions that capture demand and supply responses to policy-induced changes in relative prices.

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[22] For a detailed algebraic model description see Böhringer et al. (2018).

Primary factors of production include labor and capital, which are assumed to be mobile across sectors within each region but not internationally mobile. In fossil fuel production, part of the capital is treated as a sector-specific resource (identically to the formulation in Section 2.4). The production of goods other than fossil fuels is represented on the input side through a four-level nested constant-elasticity-of-substitution (CES) function, as illustrated in Figure 2. At the top level, an aggregate of value-added and energy is combined in fixed proportions with an aggregate of intermediate material inputs. At the second level, the value-added aggregate trades off with an energy aggregate subject to a constant elasticity of substitution while all material (non-energy) inputs enter a CES material aggregate. The third level describes the substitution within the value-added aggregate between labor and capital[23] as well as the substitution within the energy aggregate between electricity and a fuel composite of coal, gas, and (refined) oil. At the fourth level, coal, gas, and oil trade off at a constant elasticity of substitution of 0.5. On the output side, production splits into supply to the domestic and export markets subject to a constant elasticity of transformation (CET). The fossil fuel production sectors (coal, gas, and crude oil) are similar, but additionally require a specific resource factor which generates upward-sloping energy supply. We test the sensitivity of model results to alternative values of key elasticities.

Production output is allocated either to the domestic market or to the export market according to a constant-elasticity-of-transformation function. Final consumption stems from a representative agent in each region who receives income from primary factors and maximizes welfare subject to a budget constraint. Substitution patterns within the consumption bundle of the representative agent are described through a nested CES function which follows the same nesting structure as production in non-fossil-fuel sectors. The consumer also substitutes between leisure and consumption, where we set the benchmark leisure demand and elasticity of substitution in line with estimates of the compensated and uncompensated labor supply elasticity, following Ballard (2000). Government and investment demand are fixed at exogenous real levels. Investment is paid by savings of the representative agent, while taxes pay for the provision of public goods and services. In-

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[23] The elasticity of substitution between labor and capital is drawn from empirical estimates by the GTAP team and typically lies between 0.5 and 1.

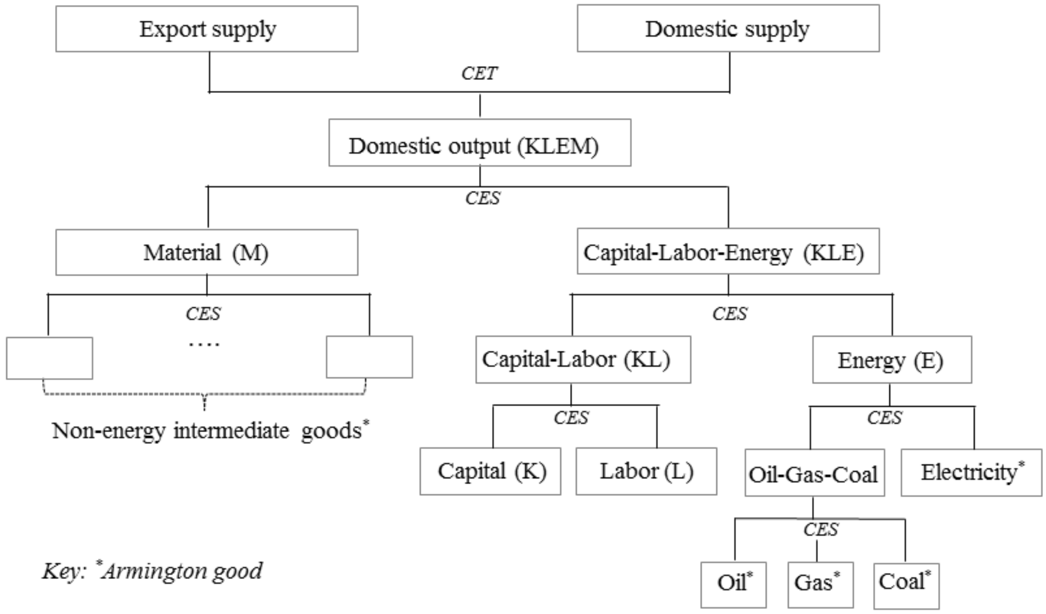

Figure 2: Production structure for non fossil goods in the CGE model

ternational trade is modeled following Armington's differentiated goods approach, where goods are distinguished by origin (Armington, 1969). The Armington composite for a traded good is a CES function of the domestic variety and an import of the same variety. The import composite, in turn, is a CES function of production from all other countries. A balance-of-payment constraint incorporates the base-year trade deficit or surplus for each region.

3.2 Data

For model parameterization we follow the standard calibration procedure in applied general equilibrium analysis. Base-year input-output data determine the free parameters of the cost and expenditure functions such that the economic flows represented in the data are consistent with the optimizing behavior of the economic agents.

We use the most recent GTAP data (GTAP9) which features national input-output tables together with bilateral trade flows across 140 regions and 57 sectors for the year 2011 (Aguiar et al., 2016). For the sake of compactness, we aggregate the GTAP dataset towards 8 sectors and 8 regions. Given our interest in energy rebound effects, we explicitly distinguish all primary and secondary energy carriers of the GTAP database: coal, gas, crude oil, refined oil products, and electricity. Furthermore, we consider three common classes of commodity classifications: agriculture, manufactured goods, and services. With respect to regions, we keep track of three geopolitically important regions that are likewise major energy consumers: the US, the EU, and China. In addition, we include a composite region featuring all remaining OECD countries, an aggregate of the (residual) G20 countries, and the composite of important oil exporting countries. All other countries in the GTAP dataset are then distinguished into either low-income countries or middle-income countries (according to standard income categories provided by the World Bank).

The responses of agents to price changes are determined by a set of exogenous elasticities taken from the pertinent econometric literature. Elasticities in international trade (Armington elasticities) and substitution possibilities in production (between primary factor inputs) are directly provided by the GTAP database. For comparability with the stylized model, we set the elasticity of substitution between energy goods and value added to 0.5 (in line with empirical estimates—see Okagawa and Ban (2008)), and vary its value in sensitivity analyses. We set $\eta_{\text{Oil}} = \eta_{\text{Gas}} = 1$ and $\eta_{\text{Coal}} = 4$ based on empirical evidence on fossil fuel supply elasticities (Graham et al., 1999; Ringlund et al., 2008; Krichene, 2002), and test the robustness of rebound effect estimates to variations in these parameters.

3.3 Results

Our CGE policy counterfactuals parallel the simulations we have undertaken with the stylized two-sector model. More specifically, we use the CGE model to estimate the rebound effect corresponding to an exogenous efficiency improvement in a particular sector and region. Following our theoretical analysis, we can decompose the rebound effect into a partial equilibrium and a general equilibrium component. We estimate the partial equilibrium rebound effect by solving the model holding all prices fixed except the price of energy services, as above. The general equilibrium component of the rebound effect is identified by a model solution in which prices return to equilibrium following the exogenous shock. We further decompose the general equilibrium component into four channels that follow from the prior discussion—a composition channel, a growth channel, a labor supply channel, and an energy price channel. Our decomposition is carried out in a way that parallels the earlier analysis with the simple model.[24] As before, the rebound is stated as the fraction of the "engineering" energy savings which is eroded by behavioural responses.

Two important features arise in the more complex general equilibrium analysis with intermediate inputs and differentiated (primary and secondary) energy carriers that are not present in the simple model outlined previously. First, goods typically embody energy both directly from energy inputs in production but also indirectly through the energy content of intermediate inputs. Our calculation of the rebound effect must account for this upstream energy consumption in order to properly decompose the rebound effect into partial and general equilibrium channels. For example, if we have energy efficiency savings in manufacturing industries in Europe, we must account for the associated indirect energy savings that result from intermediate input-output interrelations across sectors and regions. We use standard multi-region input-output (MRIO) calculus to determine the total embodied energy of goods and thus derive the total "engineering" energy savings resulting from energy efficiency improvements including both direct and indirect components (see Appendix G). Second, because energy may be transformed from primary to secondary energy carriers (e.g., crude oil is refined to produce refined petroleum products such as gasoline and diesel; natural gas is burned to produce electricity), care must be taken in estimating rebound effects to avoid double-counting energy savings. In our results below, we therefore report only energy savings and rebound in primary energy carriers—coal, crude oil, and natural gas.

Figure 3, which is the CGE analogue to the left panel of Figure 1, shows the results of simulations in which we impose a small (1%) exogenous improvement in the energy efficiency of a single sector in a single region. Here we focus on the manufacturing sector in three important geopolitical

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[24] To execute the decomposition in the general equilibrium model, we solve the CGE model separately for each rebound "channel" in which we activate the channel in question and measure the change in energy consumption. Unlike the analytical model, the CGE model is non-linear, so that the decomposition is affected by the order in which it is executed (see Harrison et al. (2000)). We report our decomposition results as a simple average over all potential decomposition orderings. In addition, we note that the while the decomposition results are sensitive to ordering, they are not strongly so, and our qualitative conclusions hold no matter what order the decomposition is executed.

regions - China, the EU, and the US.[25]

We simulate partial and general equilibrium rebound across different values for substitution elasticities in production, which we label as *lo*, *ref*, and *hi*.[26] The order of magnitude for the energy rebound in our CGE analysis is closely aligned with our earlier results obtained in the simulations with the stylized analytical two-sector model. More specifically, the reference simulation in the US manufacturing sector – in which the elasticity of substitution between energy and value added is set to 0.5 – suggests a partial equilibrium rebound of 51% and a general equilibrium rebound of about 16%, such that the total rebound effect amounts to 67%. These results are close to the outcome presented in Figure 1 for $\sigma_X = 0.5$, which suggests that our simple stylized two-sector closed economy model captures to a larger extent the key mechanisms that determine partial and general equilibrium rebound in the more complex and comprehensive CGE approach. The two approaches are also consistent in their predictions for the rebound effect as the elasticity(ies) of substitution in production are altered. With elasticities of substitution in production between energy and value-added of unity (this is the *hi* case in Figure 3), the partial equlibrium rebound is almost 100% and the total rebound is above 100%. With elasticities of substitution in production of 0.25 (the *lo* case), partial equilibrium rebound is 28% and total rebound is about 47%. Figure 3 also depicts the rebound effects with respect to exogenous improvements in the manufacturing sector energy efficiency for Europe and China which are of a similar magnitude as for the US.

When decomposing the general equilibrium rebound effect into four channels as described above, our CGE results suggest that the composition channel, the growth channel, and the energy price channel are all important contributors to the general equilibrium rebound effect, while the rebound effect through the labour supply channel is trivial in magnitude.[27] As to magnitudes,

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[25] The figure shows the results of multiple CGE simulations where we perturbate – one by one – the energy efficiency of a single sector in a single region.

[26] *Lo* elasticities are taken as half the *ref* values, while *hi* elasticities are double the *ref* values. Unlike the simple model in Section 2, the CGE model includes a more complicated nesting structure defined by a number of elasticities governing the substitutability of pairs of inputs as described above. In our simulations, we multiply the key elasticities that determine energy demand by the same factors described above. These elasticities are the elasticity of substitution between energy and value added, the elasticity of substitution between electricity and fuels, and the elasticity of substitution between coal, gas, and oil. Reference values for these elasticities are 0.5, so the *lo* and *hi* scenarios are 0.25 and 1.00 respectively.

[27] We conduct but do not report a sensitivity analysis on the effect of different labor supply elasticities on the rebound

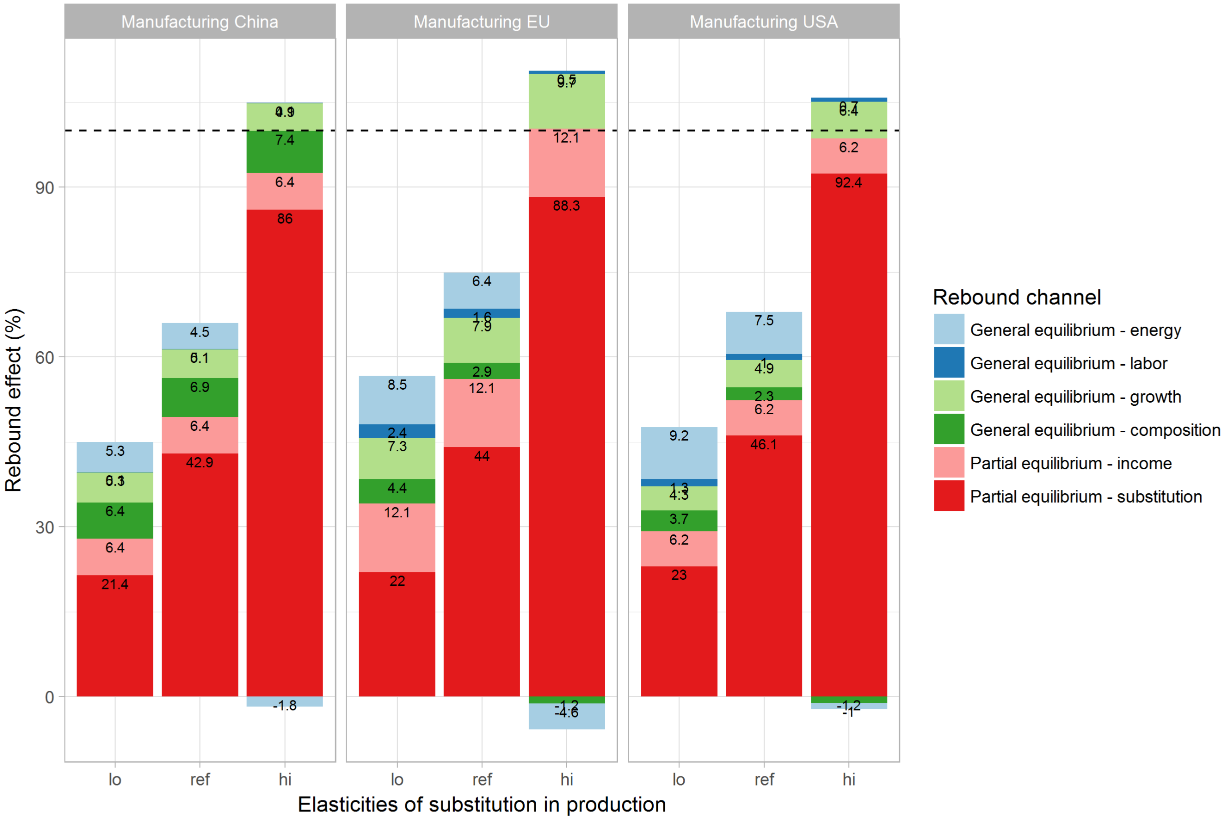

Figure 3: Rebound effect estimates from global computable general equilibrium model. The three panels illustrate the rebound effect resulting from a small improvement in the energy efficiency of the manufacturing sector in China, Europe, and the US, from left to right. The three sets of bars in each panel correspond to a sensitivity analysis over different values for substitution elasticities in production functions.

the general equilibrium rebound effect is roughly evenly divided between these three channels on average, but with differences in relative importance of the three channels for different parameters and scenarios.

Figure 4 shows estimates of partial and general equilibrium rebound in sectors other than the manufacturing sector—for China, Europe, as well as the US. There are relatively small differences between estimated rebound effects in different sector/region pairs—overall our key findings remain robust to the sector in which the energy efficiency improvement is applied.

In Figure 5, we simulate an exogenous energy efficiency improvement to a single fuel type in a particular sector-region pair. In this case, because the effective price of energy services delivered with that fuel is reduced, we would expect some substitution from other fuels to that fuel. In

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effect, as we find little impact.

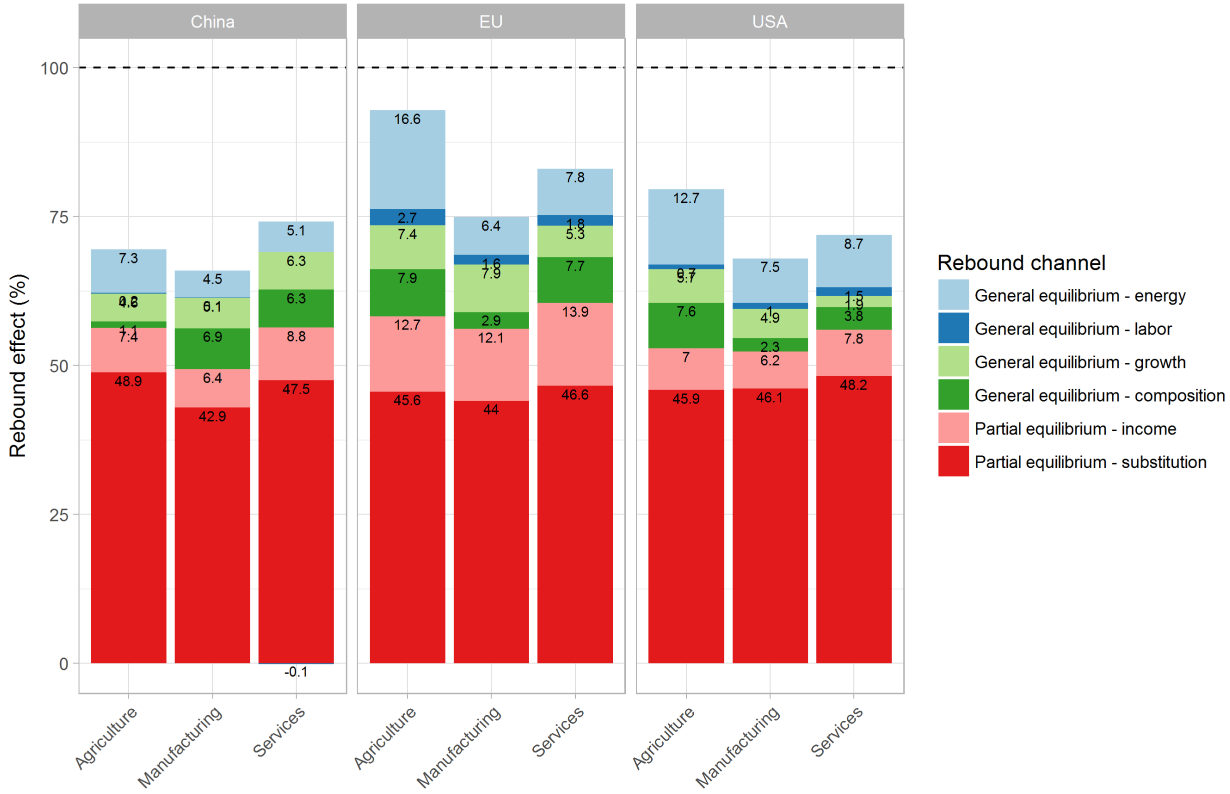

Figure 4: Rebound effect estimates from multi-sector, multi-region computable general equilibrium model. The three panels illustrate the rebound effect resulting from a small improvement in the energy efficiency of different end-use sectors in China, the EU, and the USA, from left to right.

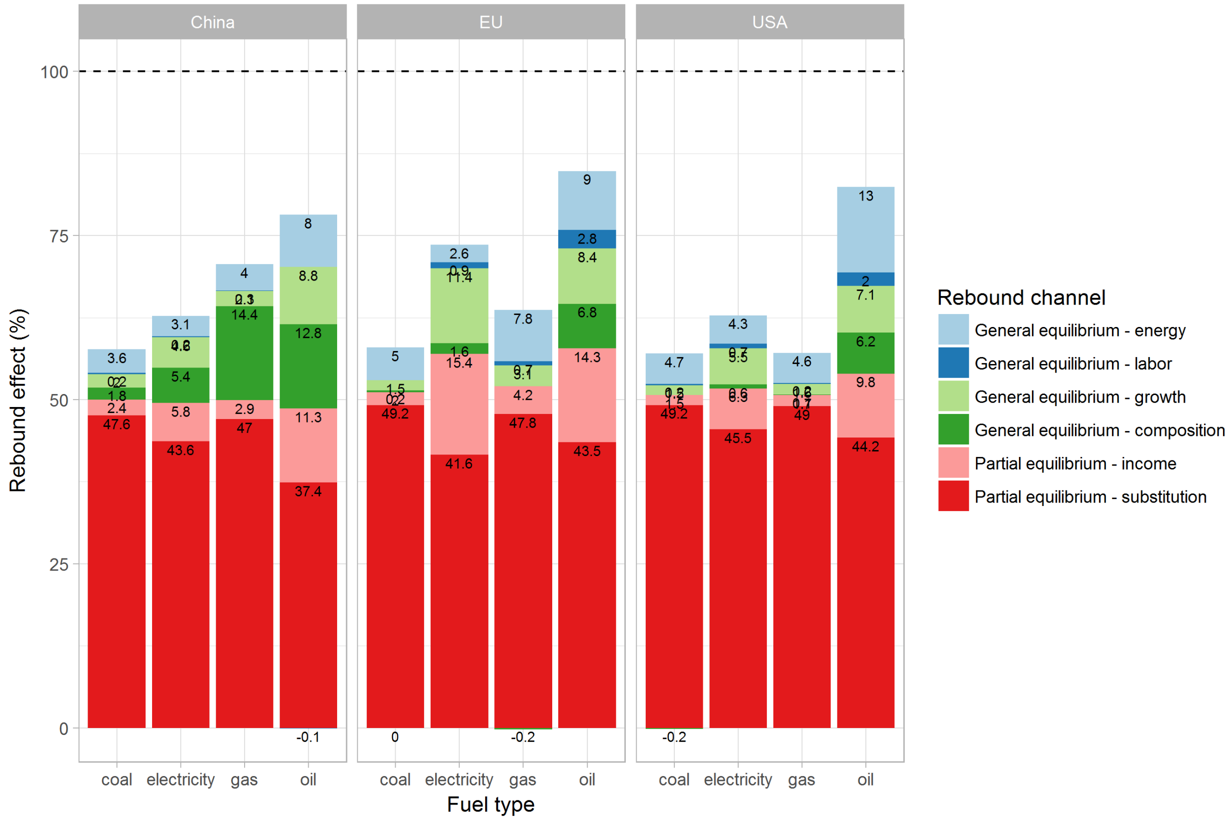

Figure 5: Rebound effect estimates from multi-sector, multi-region computable general equilibrium model. The three panels illustrate the rebound effect resulting from a small improvement in the energy efficiency of the manufacturing sector in China, the EU, and the USA, from left to right. In this figure, the energy efficiency improvement is restricted to a particular fuel type, which is identified by the horizontal axis label. Exogenous improvements to the efficiency of oil product usage refer to refined oil products (gasoline, diesel, etc.) and not crude oil itself.

addition, since the production of different fuels—such as refined oil or electricity—requires different energy resources with heterogeneous supply elasticities, we would expect differences in the rebound effect by fuel type. Figure 5 confirms that this is indeed the case. Improvements in the efficiency of refined oil product usage are associated with a substantial general equilibrium rebound effect, both because upstream energy requirements are substantial, and because the elasticity of crude oil supply is relatively low in our model. In contrast, improvements in the energy efficiency of coal usage are associated with smaller general equilibrium rebound effects, because the coal supply is relatively elastic and upstream energy requirements for coal production are smaller.

Figure 6 provides a sensitivity analysis of the rebound effect over alternative values of the

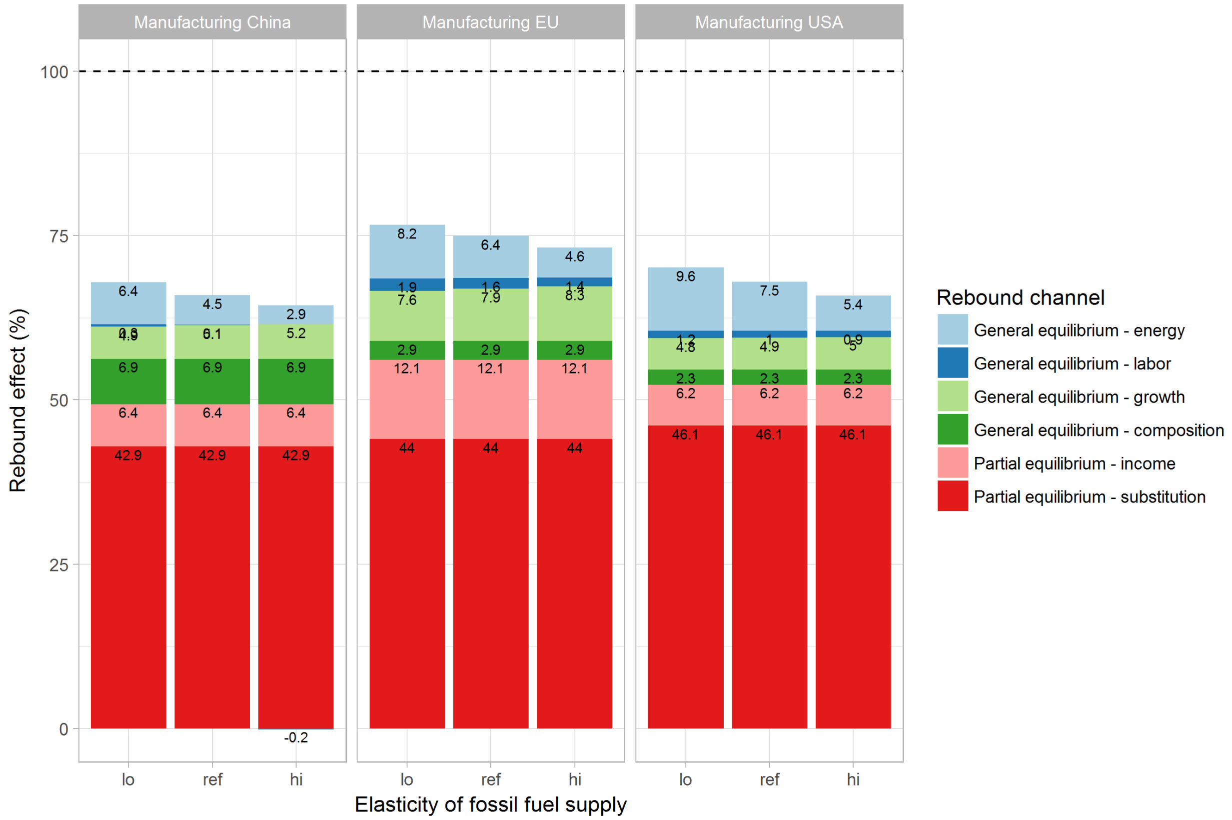

Figure 6: Sensitivity analysis of rebound effect estimates from multi-sector, multi-region computable general equilibrium model. The three panels illustrate the rebound effect resulting from a small improvement in the energy efficiency of the manufacturing sector in the US, for *lo*, *ref*, and *hi* values of fossil fuel supply elasticities, from left to right as labelled in the strip above each panel. The three sets of bars in each panel correspond to a sensitivity analysis over different values for the elasticity of supply of fossil fuels. In both cases, *lo* and *hi* correspond to half and double reference case elasticities, respectively.

fossil fuel supply elasticities. As before, the *lo* elasticities are half of reference values, and the *hi* elasticities are double the reference values. As expected, less elastic energy supply causes a larger general equilibrium rebound effect.

4 Conclusions

Energy savings provided by technological progress is widely considered as an important mechanism to address negative impacts from energy use such as anthropogenic greenhouse gas emissions associated with fossil fuel combustion. There is a long-standing literature in economics to what extent the immediate engineering energy savings from energy efficiency improvements is reduced or even overcompensated via behavioral responses emerging from price and income effects. In this paper, we have developed an analytical framework to identify key drivers of the energy rebound. In particular, our theoretical analysis provides a consistent framework to separate partial equilibrium effects (which have been the focus of the literature) from general equilibrium effects (which have been understudied so far). We show that the general equilibrium rebound effect can be decomposed into four intuitive channels reflecting the effect of energy efficiency improvements on economic composition, energy prices, economic growth, and labor supply. Important determinants of the general equilibrium component include the energy intensity and the size of the sector that receives the energy efficiency improvement, the elasticity of substitution between goods in final demand, the elasticity of substitution between capital and energy, and the elasticity of fuel supply. Our stylized analytical model can be easily populated with a few numbers from national accounts to derive rough estimates on the relative magnitude of partial versus general equilibrium rebound components. We find that over a realistic range of central parameters both partial and general equilibrium components of the rebound effect are considerable. Moreover, three of the four channels of the general equilibrium rebound effect that we identify are important contributors to the overall general equilibrium rebound effect (the labor supply channel appears rather negligible). We have conducted complementary analysis of the rebound effect with a large-scale multi-sector multi-region CGE model of global trade and energy use calibrated to empirical data. The numerical CGE substantiates the findings from our analytical model: both partial and general equilibrium components of the rebound effect are likely to be substantial, but backfire is unlikely unless energy service demand elasticities are above widely-accepted values.

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A Benchmark analytical model

This section presents the simple benchmark analytical model in differenced form (i.e., $\hat{X} = \frac{\Delta X}{X}$). We derive the differenced equations from production functions, zero-profit conditions, and market clearance conditions following Jones (1965). Note the in the equations below, the Greek symbols α, ω, and θ reflect benchmark cost shares, while the Greek symbols σ denote elasticities of substitution. Latin letters refer to prices and quantities.

The production function for sector X is $X = X(V_X, S_X)$. In differenced form, this is:

$$\hat{X} = \theta_{XV}\hat{V}_X + \theta_{XS}\hat{S}_X, \tag{7}$$

where θ_{XV} and θ_{XS} are respectively the benchmark cost shares for value-added and energy services in sector X production, and where $\hat{V}_X$ and $\hat{S}_X$ are the percent change in the demand for the value-added input and energy services by sector X. The production function for energy is linear in the value-added input, i.e.:

$$\hat{E} = \hat{V}_E. \tag{8}$$

In equilibrium, production sectors generate zero profit. The zero profit conditions for the X and E sectors are given by:

$$\hat{p}_X = \theta_{XK}\hat{p}_V + \theta_{XS}\hat{p}_{SX} \tag{9}$$

$$\hat{p}_E = \hat{p}_V, \tag{10}$$

where $\hat{p}_X$, $\hat{p}_V$, $\hat{p}_E$, and $\hat{p}_{SX}$ are the prices for good X, the value-added aggregate, energy, and energy services to sector X respectively.

The elasticity of substitution in sector X, denoted σ_X, is defined as follows, and reflects the first-order conditions for sector X. An increase in $\hat{A}_X$ increases the quantity of energy service produced by a unit of energy, as well as reduces the effective price of energy services:

$$\hat{S}_X - \hat{V}_X = \sigma_X(\hat{p}_V - \hat{p}_{SX}). \tag{11}$$

The relationship between energy services and physical energy demands is given by the following equations, where $\hat{A}_X$ represents a costless improvement in the energy efficiency of sector X:

$$\hat{S}_X = \hat{A}_X + \hat{E}_X \tag{12}$$

$$\hat{p}_{SX} = \hat{p}_E - \hat{A}_X. \tag{13}$$

Finally, in equilibrium, the markets for the value-added factor clears, such that:

$$0 = \alpha_X \hat{V}_X + \alpha_E \hat{V}_E, \tag{14}$$

where α_X and α_E are the benchmark shares of the factor input demanded by each sector. Moreover, since there is only one sector in this simple model, market clearance for the energy good requires that $\hat{E} = \hat{E}_X$ (we use this notation for continuity with the later models, in which we add additional energy-using sectors).

We set $\hat{p}_V = 0$ as the numeraire (and drop the income balance condition, which is not presented). We thus have a system of 8 linear equations and 8 unknowns, which we can solve to yield the change in total energy consumption due to an exogenous change in the energy efficiency of sector X:

$$\frac{\hat{E}}{\hat{A}_X} = -1 + \theta_{XV}\sigma_X + \alpha_X. \tag{15}$$

We can decompose this change in energy consumption due to an exogenous energy efficiency improvement as described in the main text. First, we calculate the *engineering savings* by assuming that there are no price changes following the energy efficiency improvement. Setting all price changes to zero in the equations above and using equation (8), (11), (12), and (14) yields $\frac{\hat{E}}{\hat{A}_X} = -1$. That is, with no behavioural or market response, a one-percent improvement the energy efficiency of the X sector yields an equivalent change in total energy consumption. Next we capture energy demand changes arising through the *partial equilibrium substitution channel* by allowing the price of energy services (p_{SX}) to change following the energy efficiency improvement, but holding income and other prices fixed. Solving equations (7), (8), (11), (12), (13), and (14) with all prices except p_{SX} held fixed and income held fixed (which implies $\hat{X} = 0$) yields $\frac{\hat{E}}{\hat{A}_X} = -1 + \theta_{XV}\sigma_X$. Thus, consumer substitution into the X good following the decline in its price offsets a portion of the original energy savings as described in the main text. Finally, we obtain the change in energy consumption from the *partial equilibrium income channel* by allowing changes in income following the introduction of the exogenous price change, but still holding other prices fixed. This yields: $\frac{\hat{E}}{\hat{A}_X} = -1 + \theta_{XV}\sigma_X + \alpha_E$. We use this same approach in the models that follow to decompose the partial equilibrium components of the rebound effect. The general equilibrium rebound effect is the full change in energy consumption (solved with no constraints on prices or income) less the partial equilibrium change in energy consumption. As stated in the main text, in this simple model, the general equilibrium component of the rebound effect is zero.

B Model with multiple sectors: General equilibrium composition channel

We modify the model in Appendix A to include multiple sectors. Production functions for sectors X and Y are given by:

$$\hat{X} = \theta_{XV}\hat{V}_X + \theta_{XS}\hat{S}_X \tag{16}$$

$$\hat{Y} = \theta_{YV}\hat{V}_Y + \theta_{YS}\hat{S}_Y, \tag{17}$$

where θ_{iV} and θ_{iS} are respectively the benchmark cost shares for the value-added input and energy services in sector i production, and where $\hat{V}_i$ and $\hat{S}_i$ are the percent change in the demand for value-added and energy services by sector i. The production function for energy is linear in capital inputs:

$$\hat{E} = \hat{V}_E. \tag{18}$$

In equilibrium, all production sectors generate zero profit. The zero profit conditions are given by:

$$\hat{p}_X = \theta_{XV}\hat{p}_V + \theta_{XS}\hat{p}_{SX} \tag{19}$$

$$\hat{p}_Y = \theta_{YV}\hat{p}_V + \theta_{YS}\hat{p}_{SY} \tag{20}$$

$$\hat{p}_E = \hat{p}_V, \tag{21}$$

where $\hat{p}_X$, $\hat{p}_Y$, $\hat{p}_V$, $\hat{p}_E$, $\hat{p}_{SX}$, and $\hat{p}_{SY}$ are the prices for goods X and Y, value-added, energy, and energy services to sector X and Y, respectively.

The elasticities of substitution in sector X and Y are defined as follows:

$$\hat{S}_X - \hat{V}_X = \sigma_X(\hat{p}_V - \hat{p}_{SX}) \tag{22}$$

$$\hat{S}_Y - \hat{V}_Y = \sigma_Y(\hat{p}_V - \hat{p}_{SY}), \tag{23}$$

while the elasticity of substitution in consumption is defined by:

$$\hat{X} - \hat{Y} = \sigma_U(\hat{p}_Y - \hat{p}_X). \tag{24}$$

The relationship between energy services and physical energy demands is given by the following equations, where $\hat{A}_X$ represents a costless improvement in the energy efficiency of sector X:

$$\hat{S}_X = \hat{A}_X + \hat{E}_X \tag{25}$$

$$\hat{S}_Y = \hat{E}_Y \tag{26}$$

$$\hat{p}_{SX} = \hat{p}_E - \hat{A}_X \tag{27}$$

$$\hat{p}_{SY} = \hat{p}_E. \tag{28}$$

Finally, in equilibrium, the markets for the value-added factor and energy clear:

$$0 = \alpha_X \hat{V}_X + \alpha_Y \hat{V}_Y + \alpha_E \hat{V}_E, \tag{29}$$

and

$$\omega_X \hat{E}_X + \omega_Y \hat{E}_Y = \hat{E}, \tag{30}$$

where α_i and ω_i are the benchmark shares of the value-added aggregate and energy consumed by sector i in total (economy-wide) and energy demand, respectively.

We set $\hat{p}_V = 0$ as the numeraire (and drop the budget balance equation, which we do not present), leaving us with 15 equations and 15 unknowns, which we solve to obtain:

$$\frac{\hat{E}}{\hat{A}_X} = -\omega_X + \omega_X \theta_{XV} \sigma_X + \alpha_E \omega_X + \sigma_U \omega_Y \frac{\theta_{XS}}{\theta_{YS}} (\alpha_E - \theta_{YS}). \tag{31}$$

In the main body of the text, we define the parameter $\psi \equiv \frac{\omega_Y \theta_{XS}}{\omega_X \theta_{YS}}$ as the benchmark output of sector Y compared to that of sector X.

C Model with decreasing returns in energy supply: General equilibrium energy price channel

To obtain a model in which the production of energy exhibits declining returns to scale, we modify the model in Appendix A by imposing the condition that the production energy requires the input of a fixed factor, Z, in addition to value added (i.e., $E = E(V_E, Z)$). With this assumption, the production function for energy becomes:

$$\hat{E} = \theta_{EV}\hat{V}_E, \tag{32}$$

where θ_{EV} is the cost share of the value-added factor in energy production. The associated zero profit condition is:

$$\hat{p}_E = \theta_{EV}\hat{p}_V + \theta_{EZ}\hat{p}_Z, \tag{33}$$

where $\theta_{EZ} = 1 - \theta_{EV}$ is the cost share of the fixed factor in energy production.

We must add an equation to capture substitution between value-added and the fixed factor in energy production:

$$\hat{V}_E = \sigma_E(\hat{p}_Z - \hat{p}_V), \tag{34}$$

where σ_E is the elasticity of substitution between the fixed factor and the value-added input in energy production. Rearranging yields an expression for the energy supply elasticity η:

$$\eta \equiv \frac{\hat{E}}{\hat{p}_E} = \frac{\theta_{EV}}{1 - \theta_{EV}}\sigma_E.$$

As before, we solve the model following an exogenous shock to the energy efficiency of energy services provision:

$$\frac{\hat{E}}{\hat{A}_X} = \frac{-1+\sigma_X}{1+\frac{\alpha_E}{1-\alpha_E}\frac{1}{\theta_{EV}}+\frac{1}{\eta}\sigma_X}. \tag{35}$$

D Model with endogenous capital stock: General equilibrium growth channel

We make several changes to the basic model in order to generate an algebraic solution to the model in which the capital stock is endogenous. First, we differentiate the value-added factor into its components capital and labor. We assume that both the consumption good and the investment good are X, and impose the steady-state condition that changes in the price of the investment good, p_X, must be equal to changes in the price of the capital good p_K. This condition is satisfied by allowing the capital stock to become endogenous. The full linearized model is thus given by the X production function:

$$\hat{X} = \theta_{XV}\hat{V}_X + \theta_{XS}\hat{S}_X, \tag{36}$$

where $\hat{V}$ is value added, which is produced from capital and labor:

$$\hat{V} = \theta_{VK}\hat{K} + \theta_{VL}\hat{L}. \tag{37}$$

As before, energy is produced using a linear technology with value added as an input:

$$\hat{E} = \hat{V}_E. \tag{38}$$

Zero-profit conditions for the X sector, the E sector, and the value-added activity require that:

$$\hat{p}_X = \theta_{XV}\hat{p}_V + \theta_{XS}\hat{p}_{SX} \tag{39}$$

$$\hat{p}_V = \theta_{VK}\hat{p}_K + \theta_{VL}\hat{p}_L \tag{40}$$

$$\hat{p}_E = \hat{p}_V. \tag{41}$$

Elasticities of substitution in X production and value added are defined such that:

$$\hat{S}_X - \hat{V}_X = \sigma_X(\hat{p}_V - \hat{p}_{SX}) \tag{42}$$

$$\hat{K} - \hat{L} = \sigma_V(\hat{p}_L - \hat{p}_K). \tag{43}$$

Energy services are defined identically to the model above:

$$\hat{S}_X = \hat{A}_X + \hat{E} \tag{44}$$

$$\hat{p}_{SX} = \hat{p}_E - \hat{A}_X. \tag{45}$$

The value-added market clearance condition and the labor-market clearance condition (based on the assumption that the stock of labor is exogenous) are:

$$\hat{V} = (1-\alpha_E)\hat{V}_X + \alpha_E\hat{V}_E \tag{46}$$

$$\hat{L} = 0, \tag{47}$$

and the steady-state closure condition is added, which imposes that the change in the return on capital are matched by changes in the price of the investment good:

$$\hat{p}_K = \hat{p}_X. \tag{48}$$

Setting $\hat{p}_L = 0$ as the numeraire leaves 13 linear equations and 13 unknowns. Solving the system of equations generates the change in energy consumption caused by an exogenous energy efficiency improvement:

$$\frac{\hat{E}}{\hat{A}_X} = -1 + \sigma_X\theta_{XV} + \alpha_E + \frac{\theta_{VK}}{1-\theta_{VK}}\alpha_E\sigma_V. \tag{49}$$

E Model with endogenous labor supply: General equilibrium labor supply channel

We make several changes to the basic model in order to generate an algebraic solution to the model in which the labor supply is endogenous. As in the prior model, we differentiate the value-added factor into its components capital and labor. The capital stock is fixed, while the labor supply is endogenous. The labor supply is determined by modeling the household's choice between consumption and leisure. The full linearized model is thus given by the *X* production function:

$$\hat{X} = \theta_{XV}\hat{V}_X + \theta_{XS}\hat{S}_X, \tag{50}$$

where $\hat{V}$ is value added, which is produced from capital and labor:

$$\hat{V} = \theta_{VK}\hat{K} + \theta_{VL}\hat{L}. \tag{51}$$

As before, energy is produced using a linear technology with value added as an input:

$$\hat{E} = \hat{V}_E. \tag{52}$$

Zero-profit conditions for the *X* sector, the *E* sector, and the value-added activity require that:

$$\hat{p}_X = \theta_{XV}\hat{p}_V + \theta_{XS}\hat{p}_{SX} \tag{53}$$

$$\hat{p}_V = \theta_{VK}\hat{p}_K + \theta_{VL}\hat{p}_L \tag{54}$$

$$\hat{p}_E = \hat{p}_V. \tag{55}$$

Elasticities of substitution in X production and value added are defined such that:

$$\hat{S}_X - \hat{V}_X = \sigma_X(\hat{p}_V - \hat{p}_{SX}) \tag{56}$$

$$\hat{L} - \hat{K} = \sigma_V(\hat{p}_K - \hat{p}_L). \tag{57}$$

Energy services are defined identically to the model above:

$$\hat{S}_X = \hat{A}_X + \hat{E} \tag{58}$$

$$\hat{p}_{SX} = \hat{p}_E - \hat{A}_X. \tag{59}$$

The value-added market clearance condition and the capital-market clearance condition (based on the assumption that the stock of capital is exogenous) are:

$$\hat{V} = (1 - \alpha_E)\hat{V}_X + \alpha_E \hat{V}_E \tag{60}$$

$$\hat{K} = 0. \tag{61}$$

Finally, we model consumer choice between consumption and leisure, where the elasticity of substitution between leisure (Z) and consumption is σ_Z, such that:

$$\hat{Z} - \hat{X} = \sigma_Z(\hat{p}_X - \hat{p}_L), \tag{62}$$

where with a fixed time endowment the relationship between leisure demand and labor supply is given by:

$$0 = \theta_{TZ}\hat{Z} + \theta_{TL}\hat{L}, \tag{63}$$

where θ_{TZ} (θ_{TL}) is the benchmark share of the time endowment used for leisure (labor).

Setting $\hat{p}_L = 0$ as the numeraire leaves 13 linear equations and 13 unknowns. Solving the system of equations generates the change in energy consumption caused by an exogenous energy efficiency improvement:

$$\frac{\hat{E}}{\hat{A}_X} = \frac{-1 + \theta_{XV}\sigma_X + \sigma_Z\theta_{XS} + \left(\theta_{VK}\sigma_Z + \frac{\theta_{TL}}{\theta_{TZ}}\sigma_V\right)\frac{(1-\alpha_E)(\sigma_X-1)}{\theta_{VL}\sigma_V}}{1 + \left(\theta_{VK}\sigma_Z + \frac{\theta_{TL}}{\theta_{TZ}}\sigma_V\right)\frac{1}{\theta_{VL}\sigma_V}}. \tag{64}$$

In the main body of the text, we define the parameter $\delta \equiv \frac{\hat{X}}{\hat{V}} \equiv \left(\theta_{VK}\sigma_Z + \frac{\theta_{TL}}{\theta_{TZ}}\sigma_V\right)\frac{1}{\theta_{VL}\sigma_V}$ as the elasticity of consumption with respect to the endowment.

F Data for stylized numerical calculations

We use the 71-Industry 2010 US Bureau of Economic Analysis Supply and Use Tables to generate parameters for our simple numerical simulation model. These tables are available at `https://www.bea.gov/industry/io_annual.htm`. We take the X sector to include agriculture, mining (except for oil and gas), utilities, construction, and energy-intensive manufacturing (except for petroleum refining). We take the E sector to be oil and gas mining and petroleum refining, and the Y sector to be all other sectors. We define energy inputs as petroleum and coal products, and define capital inputs as value-added at basic price. We set the capital requirements for the E sector as equal to energy demand. In the model with a fixed factor, we assume that half the requirements for the E sector represent the fixed factor (Z). The final column labeled HH refers to composite final demand of the representative US household. Consistent with the model, we assume no energy demand directly by the household. We thus obtain the matrix of input requirements given in Table 2, which we use to produce the values in Table 1 of our paper.

	X	Y	E	HH
S	128	312		
V	1,673	12,397	440	
X				1,801
Y				12,709
Total	1,801	12,709	440	14,510

Table 2: Aggregate data for simulations with the stylized model (in billions of dollars). Source: US Bureau of Economic Analysis, 2010.

G Multi-region input-output (MRIO) analysis

In order to calculate the region- and sector-specific primary energy embodied in goods we draw on input-output accounting identities for output, imports, and international transport services in each region.

For our MRIO calculation of embodied primary energy we use the denotations listed in Table 3.

Table 3: Denotations used in the MRIO calculations

Sets and Indices	
R	Set of regions (with r denoting the set index)
I	Set of producing sectors, or equivalently, set of commodities (with i denoting the set index)
G	Set of activities, consisting of the producing sectors, public expenditure (G), investment (I) and final consumption (C) (with g denoting the set index)
J	Set of international transport services (with j denoting the set index)
Parameters	
Y_{gr}	Output in the producing sectors (for $g \in I$) and level of public expenditure, investment and final consumption (for $g \in \{G, I, C\}$) in region r
X_{isr}	Exports of commodity i from in region s to region r
M_{ir}	Imports of commodity i in region r
Z^D_{igr}	Domestic intermediate inputs of commodity i in activity g in region r
Z^M_{igr}	Imported intermediate inputs of commodity i in activity g in region r
T_{jr}	International transport service j produced in region r
T_{jisr}	Input of international transport service j to imports in sector i from region s to region r
pe_{gr}	Direct primary energy content per unit of production g in region r
Variables	
pe^Y_{gr}	Embodied primary energy per unit of production g in region r
pe^M_{ir}	Embodied primary energy per unit of imported commodity i in region r
pe^T_j	Embodied primary energy per unit of international transport service j

The total embodied primary energy of of a good is composed of the primary energy inputs used in the production of the good itself as well as of the primary energy that is necessary to produce intermediate inputs and international transport services. To calculate the total embodied primary energy (per US$ of output) we use input-output accounting identities and solve the associated linear system of equations below for the primary energy content of production activities pe^Y_{gr}, the primary energy content of imports pe^M_{ir}, and primary energy content of international transport services pe^T_j. The first set of equations (65) states that the total primary energy embodied in output $pe^Y_{gr} Y_{gr}$ of activity g in region r must be equal to the sum of direct primary energy inputs, the embodied primary energy in domestic intermediate inputs and the embodied primary energy in imported intermediate inputs. The second set of equations (66) demands total embodied primary energy in imports $pe^M_{ir}M_{ir}$ of commodity i in region r to equal the sum of the embodied primary energy of all exports from regions s to r plus the primary energy embodied in international transport services, see equation. The third set of equations (67) postulates that the embodied primary energy $pe^T_j \sum_r T_{jr}$ of international transport service j must be equal to the sum of the embodied primary energy required for the production of the international transport service across countries.

$$\forall g \forall r \qquad pe^Y_{gr}Y_{gr} = co2e_{gr} + \sum_i pe^M_{ir}Z^M_{igr} + \sum_i pe^Y_{gr}Z^D_{igr} \tag{65}$$

$$\forall i \forall r \qquad pe^M_{ir}M_{ir} = \sum_s \left(pe^Y_{is}X_{isr} + \sum_j pe^T_j T_{jisr} \right) \tag{66}$$

$$\forall j \qquad pe^T_j \sum_r T_{jr} = \sum_r pe^Y_{jr}T_{jr} \tag{67}$$

We obtain a system of $(Card(G) + Card(I)) \times Card(R) + Card(J)$ unknowns and linear equations. The MRIO model can be solved directly as a square system of equations or solved recursively using a diagonalization algorithm. The data for the parameters are provided by the GTAP 9 database.

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