Targeted Technology Strategies for Low-Carbon Economic Growth: Linking Bottom-Up and Top-Down Assessments[*]

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Abstract

This chapter investigates the consequences of policies that attempt to mitigate greenhouse gas emissions without slowing the growth of the economy by improving energy efficiency in a set of target sectors. We develop a theoretical framework that unifies bottom-up marginal abatement cost curves, partial equilibrium techno-economic simulations, and analytical general equilibrium modeling. The framework is then applied to engineering assessments of energy efficiency technology deployments in Armenia and Georgia. Our results provide a practical demonstration of how to incorporate bottom-up technology detail on energy-efficiency improvements into an economic model that is simple and easily calibrated, but whose simulations throw into sharp relief the economy-wide opportunity costs and environmental benefits of technology deployment policies. The latter reveal how MAC curves can paint a misleading picture of the true potential for both abatement and economic growth when technological improvements operate within a system of general equilibrium interactions, but also highlight how the use of their underlying data to identify technology options with large investment elasticities of productivity improvement can lead to more accurate assessments of the economic consequences of low-carbon growth strategies.

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1. Introduction

Mitigating global emissions of greenhouse gases (GHGs) to levels that avert the threat of dangerous climate change requires the active participation of developing nations. Projected 21st-century economic growth and population expansion in non-OECD countries are associated with substantial increases in GHG emissions and radiative forcing of climate which cannot be completely offset by GHG abatement in the developed world—even if the latter countries stop emitting entirely (Jacoby et al, 1997). This state of affairs has led to calls for industrializing countries to take on binding emission reduction commitments, culminating in developing nations' acceptance of abatement targets under the 2016 Paris Agreement. Yet there is continuing concern that the opportunity costs of curtailing emissions will constrain countries' economic growth, leading to a gap between mitigation commitments and actions (Victor et al., 2017). This is especially true for developing nations, given the extent to which abating GHGs may constrain their ability to lift their expanding populations out of poverty. A key question is therefore how much of a Paris-style emission reduction commitment can be met via activities that slow the growth rate of developing countries' emissions, while not hindering their expected economic growth.

Assessing the technical viability of such "low-carbon economic growth" strategies is the objective of this chapter. As noted by Jacoby et al (1998), Steward and Weiner (2001) and Aldy et al (2003) among others, the goal is to allow for a transition path in which developing countries have the "headroom" to continue economic expansion over the next two or three decades, but with declining rates of increase in emissions. For low-carbon growth to be feasible there must be activities which avoid GHG emissions but also provide "win-win" economic benefits, and large-scale deployment of energy efficient devices and processes are of particular interest in this regard (Hallegate et al, 2011, Rozenberg et al, 2013). The latter "green" investments are typically more costly than conventional technology, but they enable firms and households to use less fossil energy, simultaneously lowering emissions of GHGs such as carbon dioxide (CO_2) while generating offsetting savings on energy and other operational costs. Crucially, since a key benefit of these cost savings is improved productivity at the micro-level, sufficiently widespread deployment of efficiency-enhancing technology within a country could in principle generate an aggregate gross productivity gain. And if, in turn, the resulting stimulus to the growth of output at the macro level is large enough that it exceeds the economy-wide opportunity costs of additional expenditure on energy-efficiency investments, the result will be a net increase in GDP.

How might such an auspicious outcome arise? From a purely technical standpoint, the largest potential for win-wins should come from intensive investment in technology options which have a high elasticity of energy efficiency improvement with respect to the incremental cost of their acquisition. From a behavioral standpoint, there must be some force at work deterring private actors from adopting these supposedly productive technologies without regulatory intervention. Engineering assessments (e.g., McKinsey, 2010) are the key data source on technologies' performance and direct cost characteristics which allow decision makers to identify such options. Such analyses frequently uncover what appear to be large energy efficiency gaps (so-called "investment inefficiencies"—Allcott and Greenstone, 2012; Gillingham and Palmer, 2014; Gerarden et al, 2017) in which technical potential for energy conservation remain unrealized due to factors such as imperfect information or institutional constraints, which cause economic actors to systematically overlook making energy efficiency investments that are privately profitable. By contrast, microeconomic analyses contend that the actual magnitude of the energy efficiency gap is small because engineering studies suffer from problems of potentially substantial unobserved or mis-measured ancillary costs, uncertainty in projections of the net present value of future energy cost savings, and heterogeneity among agents in the returns to energy efficiency investments (Gerarden et al, 2017).

In the face of conflicting information policymakers face the challenge of (i) identifying putatively negative net cost—so-called "no-regret"—technology options whose savings exceed the corresponding investment cost premia at prevailing capital and energy prices, (ii) estimating these options' market penetration potential and attendant fossil fuel/GHG emission savings based on economic as well as technical fundamentals, and (iii) assessing the implications for emissions, output and welfare at the level of the macroeconomy. Addressing these is a tall order, principally because of the difficulty reconciling often incommensurate results of engineering and economic calculations across what often end up being three disparate sets of analyses. This is the essence of the "bottom-up" versus "top-down" divide in the climate policy literature.

The majority of analyses stop at stage (i). Their customary approach is to develop marginal abatement cost (MAC) curves that rank, using engineering cost assessments and discounted cash flow analysis, various technology options or activities based on their net costs and avoided GHG emissions. MAC curves are attractive because they are easy to construct and bring to light activities that are profitable from the perspective of private actors investing in an individual technology. However, such analyses often fail to adequately account for the true opportunity cost of investments in technologies. They also ignore the potential substitutability or complementarity among different technologies which determines the latter's market penetration. Of concern are unforeseen interdependencies among mitigation options' cost or technical potential that render the shape of the MAC curve endogenous, where the width or height of one segment on the curve can influence the width or height of other segments, and their joint marginal-cost ranking.

Stage (ii) analyses are able to account for potential interdependencies through the use of partial equilibrium techno-economic process or activity analysis models. The latter incorporate data on the cost and energy use characteristics of a broad array of discrete technology options, and solve for the minimum cost vector of activity-specific capacities and associated emission reductions in one or more economic sectors. But these models omit interactions between the specific technnologies and the broader economy—especially the feedback effects on demand on fuel prices and capital rental rates—and must often employ ad-hoc constraints to smooth activities' time-paths of penetration or exogenously their technical potentials. It is here that the institutional or market barriers discussed above come in. The latter raise the issue of why a country might need to pursue low-carbon technology deployment policies in the first place—in other words, why the investment decisions of decentralized profit-maximizing firms would diverge from the command optimum solved for by the model, establishing the magnitude of the inefficiency gap to be closed by policy interventions such as subsidies or mandates.

Systematic accounting for the web of spillover effects is the strength of computable general equilibrium (CGE) simulations, which are the principal tool for conducing stage (iii) analyses of the macroeconomic costs of GHG mitigation policies. However, these top-down economic models struggle to incorporate the detailed characteristics of discrete technology options within the framework of smooth cost and expenditure functions customarily used to represent the envelope of firms' and households' substitution possibilities. This challenge has spawned the development of hybrid bottom-up/top-down modeling approaches which represent discrete mitigation options as production functions that generate GHG-free energy (abated emissions) from inputs of GHG-intensive fossil fuels (unabated emissions) and technology-specific abatement capital. Recent methodological advances (e.g., Kiulia and Rutherford, 2013a,b) derive the underlying abatement potentials and capital input requirements from MAC curves, but substantial calibration effort is required, and the resulting computational schemes do little to elucidate which options have the greatest potential for capital-fuel substitutability and market penetration, or the macroeconomic impacts of deploying different subsets of the available technologies.

The specific question we address is deceptively simple: what are the conditions under which countries can hope to pursue GHG mitigation without slowing down their expected economic growth, and what how much abatement can be expected in such circumstances? To provide answers we first develop a theoretical framework that unifies stage (i), (ii) and (iii) analyses by consistently tying together the underpinnings of MAC curves, bottom-up techno-economic simulation modeling, and analytical geneneral equilibrium modeling. We then apply this framework to bottom-up engineering assessments of technology deployment for improving energy efficiency in Armenia and Georgia, drawing on detailed data developed by Timilsina et al (2017). Incorporating this information into a numerically calibrated version of our analytical general equilibrium model allows us to transparently compare the economy-wide economic costs and mitigation benefits of stylized technology deployment policies in our two case-study countries. Our results illustrate how the exogenous trajectories of efficiency penetration that underlie the construction of bottom-up MAC curves can paint a misleading picture of the potential for pursuing GHG abatement while maintaining economic growth when energy efficiency mandates operate within a system of general equilibrium interactions. But they also highlight how the use of the data that underpins MAC curves—*not* the curves themselves—to identify energy efficiency improvement options with high cost elasticities of energy productivity can facilitate assessments of the macroeconomic consequences of technology strategies for low-carbon growth.

The remainder of the chapter is divided into four sections. Section 2 develops our theoretical framework, extending the analysis of Sue Wing and Timilsina (2016) to construct and explore the implications of an analytical general equilibrium model. Section 3 introduces our bottom-up Armenia and Georgia case studies, numerical calibration strategy, and simulation results. Section 4 concludes with a discussion of caveats to the analysis and future research directions.

2. Bottom-Up vs. Top-Down: A Unifying Framework

2.1. Marginal Abatement Cost Curves: Engineering Fundamentals

Our unit of analysis a vector of technology options, indexed by θ. For example, θ can indicate building shell technologies, lighting or space conditioning devices. For any such option let there be two technology variants, a conventional and a high-efficiency variety, the second of which we identify using an asterisk (*). The installed bases of each variety are x and x^* units, and differences in their service lives (ℓ, ℓ^*) translate into distinct capital recovery factors (denoted ρ). Moreover, the cost of capital acquisition is typically lower for the conventional variety ($h < h^*$), which determines the value of the technology's installed capital base as

$$v_\theta = \rho[\ell_\theta]h_\theta x_\theta + \rho[\ell^*_\theta]h^*_\theta x^*_\theta \tag{1}$$

The key distinction between conventional and high-efficiency varieties is the intensity of their fuel use ($\phi > \phi^*$), with the technology's total use of fuel type e given by

$$f_{e,\theta} = \phi_{e,\theta}x_\theta + \phi^*_{e,\theta}x^*_\theta \tag{2}$$

Introducing $t \in [0, T]$ as an index of time, ε_e as fuel-specific emission factors, and $\overline{PF}_{e,t}$ as exogenous trajectories of fuel prices, eqs. (1) and (2) determine the technology's instantaneous operating cost and emissions as weighted sums of the stocks of conventional and high-efficiency varieties:

$$\begin{aligned} c_{\theta,t} &= c_\theta[x_{\theta,t}, x^*_{\theta,t}] = v_{\theta,t} + \textstyle\sum_e \overline{PF}_{e,t} f_{e,\theta,t} \\ &= \{\rho[\ell_\theta]h_\theta + \textstyle\sum_e \overline{PF}_{e,t}\phi_{e,\theta}\}x_{\theta,t} + \{\rho[\ell^*_\theta]h^*_\theta + \textstyle\sum_e \overline{PF}_{e,t}\phi^*_{e,\theta}\}x^*_{\theta,t} \end{aligned} \tag{3}$$

$$\begin{aligned} z_{\theta,t} &= z_\theta[x_{\theta,t}, x^*_{\theta,t}] \\ &= \{\textstyle\sum_e \varepsilon_e\phi_{e,\theta}\}x_{\theta,t} + \{\textstyle\sum_e \varepsilon_e\phi^*_{e,\theta}\}x^*_{\theta,t} \end{aligned} \tag{4}$$

Given a discount factor β^t, the economic and environmental performance of a particular scenario of technology penetration $\langle x_\theta, x_\theta^* \rangle$ can be summarized by the present values of the trajectories of cost and emissions, respectively:

$$\mathcal{C}_\theta = \sum_{t=0}^{T} \beta^t c_\theta[x_{\theta,t}, x_{\theta,t}^*] \tag{5}$$

$$\mathcal{Z}_\theta = \sum_{t=0}^{T} \beta^t z_\theta[x_{\theta,t}, x_{\theta,t}^*] \tag{6}$$

In this bottom-up setting the customary representation of enegy conservation or emission reduction mandates is an exogenous shift in the mix of capital toward increased penetration of the high-efficiency variety. Let the nomenclature in (1)-(6) identify some business-as-usual (BAU) state of the world without mitigation. Now introduce a tilde over a variable to indicate the counterfactual imposition of emission mitigation, with new technology trajectories $(\tilde{x}_\theta, \tilde{x}_\theta^*)$ in which conventional capital is deiplaced by its efficienct alternative: $\tilde{x}_\theta \leq x_\theta$ and $\tilde{x}_\theta^* > x_\theta^*$. The impact of the resulting sequence of instantaneous cost and emissions can be summarized in the same way as (5) and (6): $\tilde{\mathcal{C}}_\theta = \sum_{t=0}^{T} \beta^t c_\theta\left[\tilde{x}_{\theta,t}, \tilde{x}_{\theta,t}^*\right] \leq \mathcal{C}_\theta$ and $\tilde{\mathcal{Z}}_\theta = \sum_{t=0}^{T} \beta^t z_\theta[\tilde{x}_{\theta,t}, \tilde{x}_{\theta,t}^*] < \mathcal{Z}_\theta$. Constructing a MAC curve from the baseline and counterfactual versions of (5) and (6) is a straightforward procedure. For each technology option, abatement (A) and its average cost (τ) are simply

$$A_\theta = \mathcal{Z}_\theta - \tilde{\mathcal{Z}}_\theta > 0 \tag{7}$$

$$\tau_\theta = (\tilde{\mathcal{C}}_\theta - \mathcal{C}_\theta)/(\mathcal{Z}_\theta - \tilde{\mathcal{Z}}_\theta) > 0, \tag{8}$$

and all that is necessary is to rank-order elements of θ from low to high values of τ and plot their coordinates in τ-A space.

2.2. Technology Penetration as Capital-Fuel Substitution

Our exposition lays bare how negative-cost segments of a MAC curve might arise. These are called no-regret options because they are no net direct costs to pursuing the requisite investments—at least in this partial equilibrium setting. The high-efficiency variety's larger acquisition costs increase capital charges ($\tilde{v}_\theta > v_\theta$) at the same time as its lower fuel intensities reduce fuel expenditures ($\tilde{f}_{e,\theta} < f_{e,\theta}$). When the latter outweighs the former, instantaneous total cost dips below its baseline level ($\tilde{c}_{\theta,t} < c_{\theta,t}$); if such a divergence is sufficiently large and persistent the numerator of (8) will be negative. Such behavior emerges out of the parameter combinations in curly braces in eqs. (3) and (4), and their interaction with scenarios of energy-efficient technology penetration $\langle x_\theta, x_\theta^* \rangle$ versus $\langle \tilde{x}_\theta, \tilde{x}_\theta^* \rangle$.

It should also be clear that the force driving the technology dynamics that give the MAC curve its shape is the instantaneous substitution of capital for fuel. This is apparent from (3), which can be rearranged to yield

$$\underbrace{\frac{\tilde{c}_\theta}{c_\theta}}_{\text{¤}<1} = (1 - \varpi_\theta^F) \underbrace{\frac{\tilde{v}_\theta}{v_\theta}}_{>1} + \varpi_\theta^F \underbrace{\frac{\tilde{z}_\theta}{z_\theta}}_{<1} \underbrace{\frac{\tilde{\pi}_\theta}{\pi_\theta}}_{\text{¤}1} \tag{9}$$

Here, ϖ^F is the baseline share of fuel in the technology's operating cost, π denotes the implicit average price of emissions (i.e., the total value of fuel use divided by the quantity of emissions), and the terms on the right-hand side are the (increasing) capital and (declining) fuel components of cost.[1] Total costs decline if the second term exceeds the first, which occurs where the high-efficiency alternative's capital cost premium relative to the conventional is small but its fuel use and emissions are much lower, and/or

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[1] Note that it is always the case that $\tilde{\pi}\tilde{z} < \pi z$, making the second term < 1.

fuel constitutes a large share of total operating cost. Here, however, our interest is different. We focus not on overall cost, but on the ability of capital to substitute for energy, which at the level of discrete activities is captured by the elasticity

$$\xi_\theta = \frac{d\mathrm{log}z_\theta}{d\mathrm{log}x^*_\theta} = \mathbb{E}\left[\left(\frac{\tilde{z}_\theta - z_\theta}{z_\theta}\right)/\left(\frac{\tilde{x}^*_\theta - x^*_\theta}{x^*_\theta}\right)\right] \tag{10}$$

This expression suggests that a key indicator of the overall effectiveness of technology-focused green growth policies is the aggregate ex-ante capital-energy elasticity. However, policies frequently target a broad range of activities that encompass technology options with very different service lives, user costs and future penetration scenarios. The trajectories of the often much larger stocks of conventional capital will likely differ between the baseline and policy scenarios as well, exerting an additional influence on projected energy savings. Moreover, an individual technology may lack an installed base of energy efficient varieties, rendering calculation of (10) impossible. A practical way to address both issues is aggregation—across technologies and/or types of capital. We can do so by specifying aggregate measures of instantaneous cost and emissions

$$V = \Sigma_{\mathrm{\theta}} v_\theta[x_\theta, x^*_\theta] \tag{11}$$
$$Z = \Sigma_\theta z_\theta[x_\theta, x^*_\theta] \tag{12}$$

and using them to compute the analogue of (10):

$$\bar{\xi} = \mathbb{E}\left[\left(\frac{\tilde{Z} - Z}{Z}\right)/\left(\frac{\tilde{V} - V}{V}\right)\right] \tag{13}$$

As we discuss at length below, $\bar{\xi}$, can be thought of as the reduced-form parameterization of a static innovation (technically, adoption) possibility frontier, or IPF, that defines the tradeoff between energy saving and the use of capital in production.

2.3. Beyond Scenarios: Endogenous Energy Efficiency Improvement

Two features of foregoing analysis highlight the need to transform results of bottom-up assessments if they are to be used to evaluate mitigation options' market penetration potential. Most engineering cost analyses implicitly treat the quantity and character of output of the various options as constant, which may not be the case if high-efficiency alternatives are imperfect substitutes for conventional varieties. More problematic is that costs and abatement hinge on exogenous assumptions about the time-path of investment in the high-efficiency alternative. Ceteris paribus, a technology with a more (less) aggressive trajectory will exhibit larger (smaller) discounted costs and total emissions, but due to geometric discounting the result will vary in a nonlinear fashion, with implications for mitigation options' average cost ranking and the overall shape of the MAC curve.

Following from these observations, endogenizing technologies' abatement potential and cost requires one key additional ingredient: specifying output in the form of flows of services from the conventional and energy efficient varieties, indicated by s (s^*). It is simplest to assume that production is Leontief with a fixed capital coefficient κ (κ^*), and that both supplies are perfect substitutes that fulfill an assumed exogenous time-path of aggregate service demand $\overline{\mathcal{D}}^S_{\theta,t}$, which presumably increases with projected growth of the economy. In the counterfactual scenario which is of interest here, the resulting supply-demand balance constraint is

$$\tilde{s}_{\theta,t} + \tilde{s}^*_{\theta,t} = \tilde{x}_{\theta,t}/\kappa + \tilde{x}^*_{\theta,t}/\kappa^* \geq \overline{\mathcal{D}}^S_{\theta,t} \tag{14}$$

We may then solve for the capacity trajectories by minimizing system cost while satisfying demand:

$$\langle \tilde{x}_{\theta,t}, \tilde{x}^*_{\theta,t} \rangle = \mathrm{argmin}_{\tilde{x}_{\theta,t}, \tilde{x}^*_{\theta,t}} \left\{ \textstyle\sum_\theta \tilde{\mathcal{C}}_\theta \middle| (1)-(5), (14) \right\} \tag{15}$$

This capacity expansion problem is a linear program which is at the heart of virtually all bottom-up techno-economic models. An open question is how the values of the key elasticities ξ_θ and $\bar{\xi}$ that arise from such a model's emergent behavior compare to those based technology penetration scenarios.

An unpleasant feature of the optimization problem in (15) is that capacity may exhibit unrealistic "bang-bang" behavior, switching over completely from the conventional to the energy-efficient variety in the space of one or two time-steps. This stems from the fact that there is no meaningful constraint on technology-specific capital, which in this framework is perfectly elastically supplied at the exogenous cost of capital acquisition. A common method of smoothing market penetration dynamics is to augment the problem (15) by sepicifying expansion and decline constraints, $(\underline{\gamma}, \overline{\gamma})$ and $(\underline{\gamma}^*, \overline{\gamma}^*)$, based on technology options' service lives (e.g. Vogt Schilb et al, 2014):

$$\underline{\gamma}[\ell_\theta] \leq \tilde{x}_{\theta,t+1}/\tilde{x}_{\theta,t} \leq \overline{\gamma}[\ell_\theta] \tag{16}$$

$$\underline{\gamma}^*[\ell^*_\theta] \leq \tilde{x}^*_{\theta,t+1}/\tilde{x}^*_{\theta,t} \leq \overline{\gamma}^*[\ell^*_\theta] \tag{17}$$

But the question raised by this remedy is what are the economic processes out of which these constraints arise. Evidence abounds that the true opportunity cost of even no-regrets energy efficiency investments can be substantial (Anderson and Newell, 2004), and can rise sharply as increasing quantities of output are forgone with progressive diversion of capital away from conventional production activities and toward lower-return energy saving activities. These additional costs are the true hurdle that the savings from energy efficiency improvements must clear, and the most transparent way to account for them is a general equilibrium framework.

2.4 General Equilibrium Implications

What does the outcome of eq. (15) imply for energy efficiency improvements' capacity to reduce CO_2 emissions without penalizing economic growth? To analyze the implications without explicitly representing the procedural details of capacity adjustment, we develop a simple analytical model of an economy in which exogenously accumulating jelly capital is allocated between conventional production, where it substitutes for energy, and the generation of energy efficiency improvements that increase the productivity of energy inputs. A critical aspect of rucially to a subset of economic activity. The rationale behind this setup is that, especially in emerging economies, financing constraints limit how broadly green growth policies can be applied across the economy, with the upshot that efficiency improvements tend to be targeted toward a relatively narrow range of activities or sectors. Indeed, only the most ambitious stage (i) studies examine the full range of energy supply and demand technologies across the economy.

It is straightforward to introduce targeted technology policies into the theoretical setup of Lanzi and Sue Wing's (2013) simple closed economy model. As summarized in Table 1, we assume the economy has two sectors, $i = \{A, B\}$. Each is modeled as a representative producer whose output, q_i, is generated from energy, e_i, and jelly capital, k_i, both of which are assumed to be intersectorally mobile. The economy's primary engine of growth is accumulation of broad capital, which occurs at a baseline rate, $g > 0$. A social planner decides to allocate investment between expanding the aggregate stock of directly productive jelly capital, K, and energy-efficiency capital, X, which is not directly productive, but improves the productivity of energy in the focal sector, A. Aggregate energy supply, E, is endogenous, responsive the market price of energy, p^E, with elasticity, $\psi > 0$. The prices of output and capital are p_i, and r_i, respectively. For simplicity we assume constant elasticity of substitution (CES) sectoral production technology, parameterized by elasticities of substitution, $\sigma_i \in (0,1]$ (implying that energy and capital are imperfect substitutes and both necessary inputs to production), and technical coefficients on energy inputs, α_i. Sectors' outputs are consumed by a representative agent with CES preferences, parameterized by the elasticity of substitution, $\omega \in (0,1]$ (implying that A and B are imperfect substitutes and both necessary inputs to consumption), and the coefficient on the consumption of A's product, μ.

Table 1. A stylized two-sector loglinear economy

A. Variables

	Quantities	Prices
Sectoral output	$\hat{q}_i$	$\hat{p}_i$
Sectoral energy input	$\hat{e}_i$	$\hat{p}^E$
Sectoral capital input	$\hat{k}_i$	$\hat{r}$
Aggregate utility, energy use, jelly capital	$\hat{u}, \hat{E}, \hat{K}$	
Energy efficiency capital	$\hat{X}$	

B. Benchmark Parameters

Sectoral output elasticities of energy	α_i
Sectoral capital-energy substitution elasticities	σ_i
Consumer substitution elasticity	ω
Aggregate energy supply elasticity	ψ
Shares of aggregate energy and capital used by the target sector	ϑ, λ
Share of the target sector's output in aggregation consumption	μ
Share of energy-efficiency capital in total capital endowment	χ

C. Equations

Production function, A:	$\hat{q}_A = \alpha_A(\xi\hat{X} + \hat{e}_A) + (1-\alpha_A)\hat{k}_A$	(18a)
Production function, B:	$\hat{q}_B = \alpha_B\hat{e}_B + (1-\alpha_B)\hat{k}_B$	(18b)
Zero profit condition, A:	$\hat{p}_A + \hat{q}_A = \alpha_A(\hat{p}^E + \hat{e}_A) + (1-\alpha_A)(\hat{r} + \hat{k}_A)$	(18c)
Zero profit condition, B:	$\hat{p}_B + \hat{q}_B = \alpha_B(\hat{p}^E + \hat{e}_B) + (1-\alpha_B)(\hat{r} + \hat{k}_B)$	(18d)
Input substitution, A:	$\hat{e}_A - \hat{k}_A = -\sigma_A(\hat{p}^E - \hat{r})$	(18e)
Input substitution, B:	$\hat{e}_B - \hat{k}_B = -\sigma_B(\hat{p}^E - \hat{r})$	(18f)
Utility:	$\hat{u} = \mu\hat{q}_A + (1-\mu)\hat{q}_B$	(18g)
Consumer substitution:	$\hat{q}_A - \hat{q}_B = -\omega(\hat{p}_A - \hat{p}_B)$	(18h)
Energy market clearance:	$\hat{E} = \vartheta\hat{e}_A + (1-\vartheta)\hat{e}_B = \psi\hat{p}^E$	(18i)
Capital market clearance:	$\hat{K} = \lambda\hat{k}_A + (1-\lambda)\hat{k}_B = g - \chi\hat{X}$	(18j)
Numeraire:	$\hat{r} = 0$	(18k)

Panel C summarizes the static equilibrium of the two-sector economy, specified as a system of equations in which the variables above enter in the log-differential form (indicated by a "hat"—$\hat{v} = d\log v$) which allows them to be interpreted as percentage changes. Each zone's production process is represented three sets of equations: production functions ((a) and (b)), the associated constant returns to scale (CRTS) zero-profit conditions ((c) and (d)), and the definition of the elasticities of substitution ((e) and (f)). The model's key policy parameter, $\hat{X}$, indicates the quantity of jelly capital accumulation that is diverted toward accumulation of technology-specific capital. The latter is not directly productive, but instead improves the target sector's energy efficiency according to the elasticity $\xi > 0$, resulting in energy-saving technological progress, $\xi\hat{X}$. To render the model algebraically tractable we treat the opportunity cost of efficiency improvement as falling on the entire economy through the channel of a reduced aggregate endowment of jelly capital—in (c) the cost of $\hat{X}$ is not an argument to A's cost function. Consumers are represented by two equations, a representative utility function (g) denominated over the outputs of the sectors, and the definition of the elasticity of substitution in consumption (h). The boundary conditions of the economy are the supply-demand balances for energy and jelly capital ((i) and (j)), in which the parameters ϑ and λ denote A's share of the respective aggregate endowments. The final condition (k) specifies the rental rate of capital as the numeraire.

There are two channels by which higher energy efficiency affects the economy. First, in the sector benefiting from the efficiency improvement, A, energy's marginal product exceeds its marginal opportunity cost. Thus, sector A spends an amount $\alpha_A(\hat{p}^E + \hat{e}_A)$ on energy to gain a contribution to output of $\alpha_A(\xi\hat{X} + \hat{e}_A)$, while sector B spends an amount $\alpha_B(\hat{p}^E + \hat{e}_B)$ but only gains $\alpha_B\hat{e}_B$. Consequently, A's relative output price declines and its relative output quantity rises, inducing intersectoral reallocation of energy and capital through the backward linkage of input prices, and changes in consumers' utility through the forward linkage of output quantities. The second channel is the economy-wide opportunity cost from diverting jelly capital to technology-specific capital. Starting off with a benchmark quantity of broad capital, $K^{\ddagger}$, accumulation is divided between jelly and energy-efficiency varieties (dK and dX, respectively), delineating the tradeoff between economy-growing and energy-saving investments as

$$g = \frac{dK + dX}{K^{\ddagger}} = \hat{K} + \chi\hat{X} \Rightarrow \hat{K} = g - \chi\hat{X}$$

where χ is technology-specific capital's benchmark share of broad capital. Larger $\hat{X}$ thus induces slower growth of sectoral output supply and consumption, and welfare. Together, both channels act to shift the economy to a new, counterfactual equilibrium, which is the solution to the 11 linear equations in as many unknowns, $\{\hat{p}_A, \hat{q}_A, \hat{p}_B, \hat{q}_B, \hat{e}_A, \hat{e}_B, \hat{k}_A, \hat{k}_B, \hat{p}^E, \hat{r}, \hat{u}\}$.

The analytical solution to the counterfactual equilibrium is algebraically too complicated to easily yield insights. To facilitate interpretation, in the analytical exposition that follows we consider a simplified version of the economy with common production technology in both sectors, $\alpha_A = \alpha_B = \alpha$ and $\sigma_A = \sigma_B = \sigma$.

In our baseline no-policy BAU scenario, jelly capital accumulation proceeds unfettered by energy efficiency mandates ($\hat{X} = 0$). An attractive feature of our model is that aggregate and sectoral capital stocks grow at the baseline rate ($\hat{k}_A^{BAU} = \hat{k}_B^{BAU} = g$), while energy use grows more slowly,

$$\hat{e}_A^{BAU} = \hat{e}_B^{BAU} = \hat{E}^{BAU} = \frac{\psi}{\sigma + \psi} g \tag{19}$$

and the pace of growth of sectoral output and utility lies between those of energy and capital:

$$\hat{u}^{BAU} = \hat{q}_A^{BAU} = \hat{q}_B^{BAU} = \left(1 - \frac{\alpha\sigma}{\sigma + \psi}\right) g \tag{20}$$

An advantage of our model is that it allows us to disentangle the costs and benefits of energy-efficiency improvements. The cost-only case corresponds to a situation where investment in technology-specific capital is completely unproductive ($\xi = 0$), while triggering a reduction the rate of jelly capital accumulation—$\hat{X} > 0$ in eq. (1j). The benefit-only case corresponds to "manna from heaven" costless energy-saving innovation, represented by $\hat{X} > 0$ in eq. (18a) and $\hat{X} = 0$ in (18j). Henceforth, we use Δ to denote the difference between the value of a variable in a counterfactual scenario and its corresponding value in the BAU scenario, which indicates the policy-induced change in the variable's growth rate.

Technology-specific capital investment's opportunity cost is the drag on aggregate capital accumulation ($\Delta\hat{K}^{Cost} = \Delta\hat{k}_A^{Cost} = \Delta\hat{k}_B^{Cost} = -\chi\hat{X}$), which is associated with unambiguous declines in energy use, output and welfare below BAU growth rates

$$\Delta\hat{E}^{Cost} = \Delta\hat{e}_A^{Cost} = \Delta\hat{e}_B^{Cost} = -\frac{\chi\psi}{\sigma+\psi}\hat{X} < 0 \tag{21}$$

$$\Delta\hat{u}^{Cost} = \Delta\hat{q}_A^{Cost} = \Delta\hat{q}_B^{Cost} = -\chi\left(1 - \frac{\alpha\sigma}{\sigma+\psi}\right)\hat{X} < 0 \tag{22}$$

Conversely, in the benefit-only case welfare always improves

$$\Delta\hat{u}^{Benefit} = \frac{\alpha\xi}{\sigma+\psi}\{\alpha\sigma\vartheta(1-\omega) + (\sigma+\psi)\omega\mu + (\sigma(1-\alpha)+\psi)(1-\omega)\lambda\}\hat{X} \tag{23}$$

simultaneous with unambiguous decline in the target sector's energy use and leakage which causes rest-of-economy energy consumption to unambiguously rise

$$\Delta\hat{e}_A^{Benefit} = -\frac{\alpha\xi}{\sigma+\psi}\big((1-\vartheta)\sigma + (1-\lambda)\psi\big)(1-\omega)\hat{X} < 0 \tag{24}$$

$$\Delta\hat{e}_B^{Benefit} = \frac{\alpha\xi}{\sigma+\psi}(\vartheta\sigma + \lambda\psi)(1+\omega)\hat{X} > 0 \tag{25}$$

This rebound effect means that the impact on aggregate energy use is ambiguous

$$\Delta\hat{E}^{Benefit} = -\frac{\alpha\xi}{\sigma+\psi}(\vartheta-\lambda)\psi(1-\omega)\hat{X} \tag{26}$$

with total energy consumption guaranteed to decline if the target sector's energy use as a share of aggregate energy consumption exceeds its capital input as a share of the aggregate capital endowment:

$$\vartheta > \lambda \tag{27}$$

Since policymakers have discretion regarding which economic activities will be subject to abatement measures, we assume that they define the target sectors in a way that satisfies this condition. But we shall see in the next section that this should not be taken for granted. The lesson is that (27) is a useful litmus test for policy design.

Bringing together benefits and costs, the change in welfare is proportional to accumulation of technology specific capital, but the constant of proportionality is of ambiguous sign

$$\Delta\hat{u}^{NetBenefit} = \frac{1}{\sigma+\psi}\left\{\begin{matrix}\alpha\sigma\chi + \alpha\xi(\sigma+\psi)[\omega\mu + (\sigma+\psi)(1-\omega)\lambda] \\ +\alpha^2\xi\sigma(\vartheta-\lambda)(1-\omega) - \chi(\sigma+\psi)\end{matrix}\right\}\hat{X} \tag{28}$$

Eq. (18g) sheds light on the origin of this result. Subject to the sufficient condition $\alpha\xi\omega > \chi$, technology policy affects welfare positively by expanding the target sector's output, and negatively by causing the remainder of the economy's output to contract:[2]

$$\hat{u}^{NetBenefit} = \frac{\sigma(1-\alpha)+\psi}{\sigma+\psi} g + \underbrace{\mu\big(\mathcal{L} + (\alpha\xi\omega - \chi)\big)\hat{X}}_{A\text{ channel}} - \underbrace{(1-\mu)\mathcal{L}\hat{X}}_{B\text{ channel}} \tag{29}$$

The third term in this expression represents the economy-wide opportunity cost of efficiency investments that is typically absent from MAC curve analyses.

Eq. (29) also highlights the fact that our highly simplified loglinear economy does not exhibit the concavity property that allows the expansion of technology-specific capital investment to be solved for as an endogenous variable—any $\hat{X} > 0$ will generate either a gain or loss in welfare relative to the baseline, depending on the value of the parameters. Below we emphasize that the value of $\hat{X}$ does determine the absolute magnitude of energy saving and abatement. In particular, energy efficiency improvement is welfare enhancing if the productivity elasticity of technology-specific capital investment is positive and sufficiently large, clearing the hurdle

$$\xi^{\dagger} = \xi|_{\Delta\hat{u}^{NetBenefit}=0} = \frac{\chi((1-\alpha)\sigma+\psi)}{\alpha\{\alpha\sigma(1-\omega)\vartheta + (\sigma+\psi)\omega\mu + (\sigma(1-\alpha)+\psi)(1-\omega)\lambda\}} > 0 \tag{30}$$

As we go on to elaborate below, whether the value of $\bar{\xi}$ derived from bottom-up analysis exceeds the macroeconomically-determined $\xi^{\dagger}$ is a key indicator of the likelihood of energy efficiency policies exerting a drag on projected economic growth.

The target sector consumes less energy

$$\Delta\hat{e}_A^{NetBenefit} = \frac{-1}{\sigma+\psi}\{\chi\psi + \alpha\xi\big((1-\vartheta)\sigma + (1-\lambda)\psi\big)(1-\omega)\}\hat{X} < 0 \tag{31}$$

We note that the IPF affects, but does not completely determine, the ex-post elasticity of target-sector energy saving with respect to technology-specific capital investment; its influence is modulated by the elasticities of substitution and energy supply. The change in rest-of-economy energy use is ambiguous,

$$\Delta\hat{e}_B^{NetBenefit} = \frac{-1}{\sigma+\psi}\{\chi\psi - \alpha\xi(\vartheta\sigma + \lambda\psi)(1-\omega)\}\hat{X} \tag{32}$$

declining if the benchmark fraction of aggregate capital formation allocated to energy efficient technologies is sufficiently large relative to the elasticity of technology-specific capital's productivity. The latter condition plays a key role in the response of aggregate energy consumption:

$$\Delta\hat{E}^{NetBenefit} = -\frac{\psi}{\sigma+\psi}\big(\chi + \alpha\xi(\vartheta-\lambda)(1-\omega)\big)\hat{X} \tag{33}$$

While (24) is a sufficient condition for aggregate energy conservation, the necessary condition is that the productivity elasticity clears a hurdle defined by the weighted difference between the benchmark shares

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[2] $\mathcal{L} = \frac{\alpha}{\sigma+\psi}\{\alpha\xi\sigma(\vartheta-\lambda)(1-\omega) + \sigma\chi + \lambda\xi(\sigma+\psi)(1-\omega)\}$

of the aggregate capital endowment demanded by the target sector and invested in efficiency improvement:

$$\xi > \frac{1}{\alpha\vartheta}\left(\lambda - \frac{\chi}{1-\omega}\right) \tag{34}$$

Note that if the economy is already sufficiently intensive in technology-specific capital in the baseline (i.e., $\chi > \lambda(1-\omega)$) further investment is guaranteed to bring about a fall in total energy use, even if the productivity elasticity is negligible. This is simply the cost channel at work, achieving reductions in energy use and emissions by sacrificing capital accumulation and output growth.[3]

We are now in a position to clarify the link between the bottom-up and top-down estimates of the cost of CO_2 abatement discussed in previous sections. Recall that the hallmark of no-regrets technology options is elastic substitution of capital for energy that enables the target sector's energy input demand and cost to decline by a larger amount than its capital input and cost increase, yielding negative cost MAC curve segments, and, presumably, a reduction in the sector's cost of production. The setup of the present model arrives at a similar result via a slightly different route: because the sector does not incur the cost of technology specific capital investment declines, the input and cost of jelly capital and energy both decline. In addition to (31), $\Delta\hat{p}^{\,E,NetBenefit} < 0$ and $\Delta\hat{k}_A^{NetBenefit} < 0$. If investments in energy efficiency are sufficiently productive the target sector likely benefits from an expansion in output (subject to conditions associated with (29)). A's output price declines

$$\Delta\hat{p}_A^{NetBenefit} = -\frac{\alpha}{\sigma+\psi}\left(\chi + \xi(\sigma+\psi) + \alpha\xi(\vartheta-\lambda)(1-\omega)\right)\hat{X} \tag{35}$$

moreover it does so by an amount that exceeds the increase in output, leading to a decline in the overall cost of production. Eq. (29) drives home the fact that even if we only deduct the technology-specific capital that benefits A from the stock of productive capital available to the rest of the economy, the cost output forgone as a consequence can easily outweigh the benefit to the target sector, triggering an aggregate welfare loss.

In international climate agreements, the discussion of allowing developing countries headroom to continue to expand emissions, albeit less rapidly than under BAU conditions (Jacoby et al, 1998), raises the question of what policies will be required to enable the economy's energy use to actually decline. We close by considering the level of the mandate necessary to achieve reductions in energy use and emissions in absolute terms, not merely relative to the baseline. The relevant condition is $\hat{E}^{NetBenefit} < 0$, from which we derive the threshold investment in technology-specific capital:

$$\hat{X}^{\dagger} = \frac{g}{\chi + \alpha\xi(\vartheta-\lambda)(1-\omega)} \tag{36}$$

Subject to our now-familiar sufficient condition, the intuitive result is that a less stringent policy is required the slower the baseline rate of economic growth, the higher the productivity and the larger the benchmark share of technology-specific capital, the more energy intensive the target sector, and the smaller the elasticity of substitution between the outputs of the target sector and the rest of the economy. Finally, we ask whether stabilizing emissions forecloses the possibility of economic growth in absolute terms. Surprisingly, once (27) is satisfied, the answer is unequivocally no:

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[3] This is easily verified by setting $\xi = 0$ in (31) and simplifying to obtain eq. (21).

$$\hat{u}^{NetBenefit}\Big|_{\hat{X}=\hat{X}^{\dagger}} = \frac{\alpha\xi(\omega\mu + (1-\omega)\vartheta)}{\chi + \alpha\xi(\vartheta - \lambda)(1-\omega)} g > 0 \tag{37}$$

In the following section we further examine the implications of our analysis, drawing on real-world green growth policies as a case study.

3. Policy Application: Energy-Efficiency Improvements in Georgia and Armenia

We use our analytical general equilibrium model to investigate the economic consequences of strategies to improve energy efficiency in Armenia and Georgia, where investments mandates are a major component of energy policy. Both countries depend on imports to meet domestic demand for petroleum and natural gas, which together account for more than two-thirds of their total primary energy supply, and are major sources of GHG emissions and local air pollution. Both nations have established programs to implement energy efficiency measures in major energy consuming sectors such as buildings, industries and transportation. Large-scale deployment of energy efficient technologies by the private sector remains limited and reliant on an array of government supports, raising the question of how constrained public budgets may be optimally allocated across technologies and industries. Stage (i) scoping evaluations have identified the main technology options in target sectors, and, based on their characteristics construct MAC curves (Timilsina et al, 2017), but do not go as far as characterizing the effects of energy efficiency improvements on macroeconomic outcomes. This is what we now do, using the analytical model of section 2.4.

3.1. Energy Efficiency Improvement: Technology Options and the Capital-Energy Substitution

Figure 1 provides details of the policy setting, summarizing the discrete technology options and their encompassing sectors analyzed by Timilsina et al (2017).[4] In our analytical model, these activities correspond to the target sector, A. The figure also shows the associated MAC curves. Their striking feature is the overwhelming preponderance of no-regrets options, primarily in the areas of residential appliances and insulation, which indicate potential for long-run discounted abatement in the amount of 0.67 $MTCO_2$ in Armenia and 6 $MTCO_2$ in Georgia at or below zero net cost.

Figure 2 elucidates the energy-efficiency improvement scenarios over the 2015-2034 policy horizon that underlie the MAC curves above, showing the assumed trajectories of energy efficient technology varieties relative to the baseline scenario. A substantial fraction of the assumed total abatement arises from technology options whose energy efficiency can only be increased at a significant capital cost premium (e.g., lighting in Georgia's commercial sector and both countries' commercial sectors). These options highlight the fact that although the cost reductions from energy savings outweigh the associated additional capital cost, leading to negative discounted net total costs by eq. (5), obtaining these energy savings nonetheless requires substantial investment, which in turn raises the possibility of large opportunity costs. The balance between energy savings and investment costs is captured by the capital-energy elasticities, which by eqs. (10) and (13) reflect the downward slope of the loci, and indicate the potential for the largest energy saving "bang" for the lowest direct cost "buck". Energy savings are almost uniformly inelastic, with Armenia's slate of technologies being smaller, but generally far more productive than the options available to Georgia, resulting in an aggregate capital-energy elasticity nearly 4 times as large.

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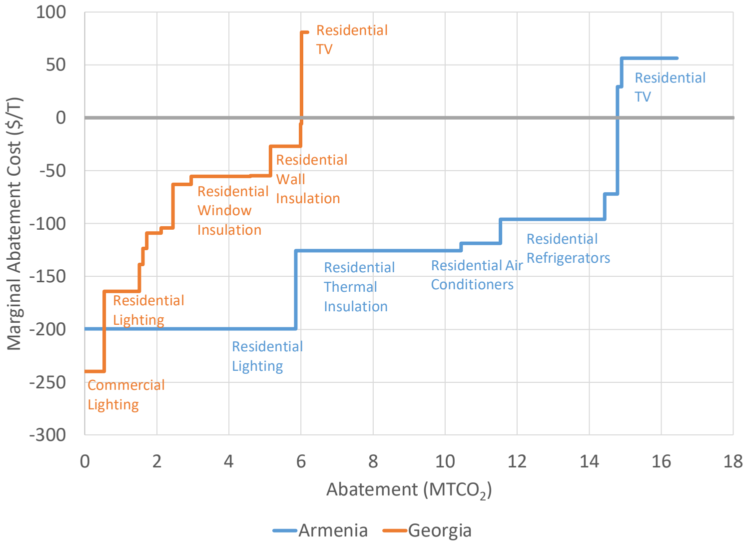
[4] Data consist of $(\ell_\theta, \ell^*_\theta)$, (h_θ, h^*_θ), $(\phi_{e,\theta}, \phi^*_{e,\theta})$ and $\varepsilon_{e,\theta}$ and assumptions about $\overline{PF}_e$, $\langle x_\theta, x^*_\theta \rangle$ and the discount rate (7.5%), which is used to calculate ρ.

3.2 Numerical Analysis

To illustrate the implications of our model, we numerically parameterize the economy in Table 1 using input-output accounts for Armenia and Georgia tabulated taken from version 8 of the Global Trade Analysis Project (GTAP) database (Narayanan et al, 2012). The target sector is assumed to be an aggregate of services[5] and private dwellings. The latter is problematic because in the economic accounts only capital, not energy is used in the production of housing services—by convention, energy use associated with residential buildings is included in the final demand vector. To construct a more precise estimates of the model parameters we adjusted the input-output tables by attributing final use of energy associated with buildings into the dwellings sector.[6]

Figure 1. Energy Efficiency in Armenia and Georgia: Technologies and Marginal CO_2 Abatement Costs

	Armenia		Georgia	
	Residential	Commercial	Residential	Commercial
Building Shell				
Windows			✓	✓
Roof Insulation			✓	✓
Wall Insulation			✓	✓
Insulation (general)	✓			
Lighting	✓	✓	✓	✓
Appliances				
Washing Machines			✓	
Refrigerators	✓		✓	
Televisions	✓		✓	
Air Conditioning	✓	✓		



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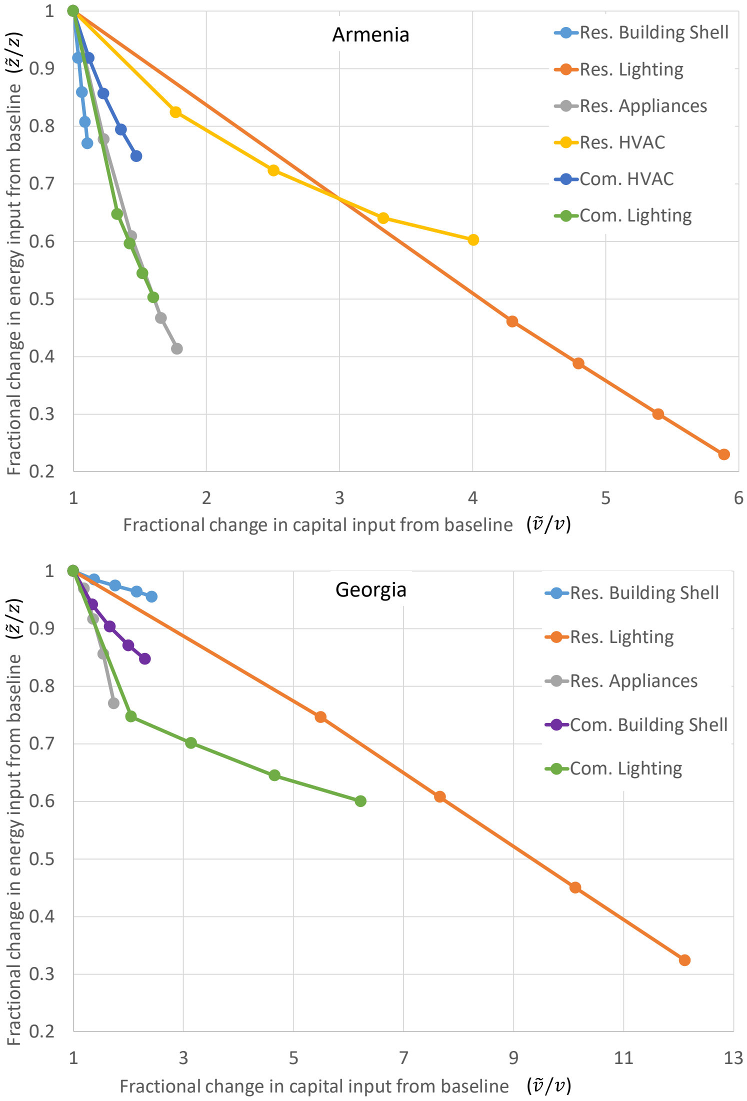
[5] We aggregated Communication, Financial services, Insurance, Business services, Recreational and other services and Public Administration, Defense, Education, Health.

[6] We assumed that building energy use accounted for 90% of final consumers' demands for electricity, natural gas and coal, and, following Paltsev et al (2004), 10% of those for oil & gas and refined petroleum.

Figure 2. Technology Penetration and Capital-Energy Substitution in Armenia and Georgia



	Armenia		Georgia	
	Residential	Commercial	Residential	Commercial
Building Shell				
Windows			0.026	0.056
Roof Insulation			0.015	0.055
Wall Insulation			0.034	0.085
Insulation (general)	–			
Lighting	0.156	0.716	0.060	0.010
Appliances				
Washing Machines			0.215	
Refrigerators	1.621		0.244	
Televisions	0.400		0.398	
Air Conditioning	0.132	0.510		
Aggregate	0.474		0.130	

The parameter values, summarized in Table 3, highlight the differences in the structure of the two economies. Both economies grow at similar rates of 3-4% per annum, and the benchmark fractions of capital input devoted to improving energy efficiency are also similar and small, around 5%, hinting at the scope for advanced technology penetration. The target commercial and private dwellings sectors are a significant fraction of total consumption (less than 35% in Georgia and 20% in Armenia). Energy's share of total production cost is small in both the target and rest-of-economy sectors, less than 12%. However, compared to Georgia, the energy intensity of Armenia's target sectors is twice as large, while that of the rest of the economy is 75% as large. Similarly, the fraction of aggregate energy consumption accounted for by the target sectors is larger in Armenia by one-third. The biggest difference is fraction of aggregate capital accounted for by the target sectors: Georgia's share exceeds 50%, over twice as large as Armenia's. Crucially, this means that our key sufficient condition (27) is satisfied for Armenia, but not for Georgia, suggesting that all of its energy savings and abatement will arise via the output growth-limiting cost channel, with correspondingly more negative welfare consequences.

Table 3. Parameterization of the economic model for Armenia and Georgia

	μ	α_A	α_B	λ	ϑ	χ	g
Armenia	0.20	0.16	0.09	0.22	0.35	0.04	0.033
Georgia	0.34	0.04	0.12	0.52	0.39	0.05	0.037

Table 4 summarizes the characteristics of the baseline trajectory. Utility, sectoral output, and aggregate and sectoral capital all grow at similar rates (2.8-3.3% in Armenia and 3.4-3.8% in Georgia), and vary only slightly over different combinations of values of the elasticity of substitution. Sectoral output prices are stable, growing an order of magnitude more slowly, but are relatively more responsive to variation in substitution possibilities (0.2-0.4% in Armenia and 0.1-0.6% in Georgia). Sectoral and aggregate energy use expand more slowly than the capital stock, with growth rates that are declining in the elasticity of energy-capital substitution and increasing in the elasticity of energy supply (1.1-2.8% in Armenia and 1.2-3.2% in Georgia).

Table 4. Business as usual growth rates (%) under different parameterizations of the economy

	Armenia				Georgia			
	$\psi = 0.5$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 1.25$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 1.25$
	$\omega = 0.25$	$\omega = 0.75$	$\omega = 0.75$	$\omega = 1$	$\omega = 0.25$	$\omega = 0.75$	$\omega = 0.75$	$\omega = 1$
	$\sigma = 0.75$	$\sigma = 1$	$\sigma = 0.25$	$\sigma = 0.25$	$\sigma = 0.75$	$\sigma = 1$	$\sigma = 0.25$	$\sigma = 0.25$
$\hat{u}$	3.1	3.1	3.2	3.3	3.5	3.4	3.6	3.6
$\hat{q}_A$	3.0	3.0	3.0	3.1	3.5	3.4	3.6	3.6
$\hat{q}_B$	3.1	3.1	3.2	3.3	3.4	3.4	3.5	3.6
$\hat{e}_A$	1.4	1.1	2.1	2.7	1.5	1.2	2.5	3.1
$\hat{e}_B$	1.3	1.1	2.2	2.8	1.5	1.2	2.5	3.1
$\hat{k}_A$	3.4	3.3	3.2	3.2	3.7	3.7	3.7	3.7
$\hat{k}_B$	3.3	3.3	3.3	3.3	3.7	3.7	3.7	3.7
$\hat{E}$	1.3	1.1	2.2	2.8	1.5	1.2	2.5	3.1
$\hat{K}$	3.3	3.3	3.3	3.3	3.7	3.7	3.7	3.7
$\hat{p}_A$	0.4	0.3	0.7	0.3	0.3	0.3	0.5	0.3
$\hat{p}_B$	0.2	0.2	0.4	0.2	0.4	0.3	0.6	0.3
$\hat{p}^E$	2.7	2.2	4.4	2.2	3.0	2.5	5.0	2.5

Table 5. Change in growth rates of economic variables from BAU with 50% expansion of energy efficiency investment ($\hat{X}$ = 0.5) under different parameterizations

A. Productivity elasticities that guarantee no welfare loss

	Armenia				Georgia			
	$\psi = 0.5$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 1.25$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 1.25$
	$\omega = 0.25$	$\omega = 0.75$	$\omega = 0.75$	$\omega = 1$	$\omega = 0.25$	$\omega = 0.75$	$\omega = 0.75$	$\omega = 1$
	$\sigma = 0.75$	$\sigma = 1$	$\sigma = 0.25$	$\sigma = 0.25$	$\sigma = 0.75$	$\sigma = 1$	$\sigma = 0.25$	$\sigma = 0.25$
$\xi^{\dagger}$	0.99	1.05	1.10	1.15	0.95	1.12	1.16	1.31
$\Delta\hat{q}_A$	1.55	4.93	5.21	7.21	0.81	2.86	2.95	4.46
$\Delta\hat{q}_B$	-0.39	-1.25	-1.32	-1.82	-0.45	-1.59	-1.65	-2.49
$\Delta\hat{e}_A$	-4.77	-2.02	-2.71	-1.49	-3.13	-1.69	-2.52	-2.13
$\Delta\hat{e}_B$	1.04	0.04	-0.68	-1.55	0.64	-0.21	-0.96	-2.12
$\Delta\hat{k}_A$	-6.35	-3.44	-3.42	-1.79	-4.37	-3.27	-3.3	-2.56
$\Delta\hat{k}_B$	-0.54	-1.38	-1.38	-1.85	-0.60	-1.78	-1.74	-2.54
$\Delta\hat{E}$	-1.05	-0.71	-1.41	-1.52	-0.83	-0.79	-1.57	-2.12
$\Delta\hat{K}$	-1.84	-1.84	-1.84	-1.84	-2.55	-2.55	-2.55	-2.55
$\Delta\hat{p}_A$	-7.98	-8.37	-8.96	-9.14	-5.22	-6.12	-6.51	-7.16
$\Delta\hat{p}_B$	-0.19	-0.13	-0.26	-0.11	-0.20	-0.19	-0.38	-0.20
$\Delta\hat{p}^E$	-2.10	-1.41	-2.82	-1.22	-1.65	-1.57	-3.13	-1.70

B. Productivity elasticities estimated based on Timilsina et al (2017)

	Armenia ($\bar{\xi} = 0.47$)				Georgia ($\bar{\xi} = 0.13$)			
	$\psi = 0.5$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 1.25$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 0.5$	$\psi = 1.25$
	$\omega = 0.25$	$\omega = 0.75$	$\omega = 0.75$	$\omega = 1$	$\omega = 0.25$	$\omega = 0.75$	$\omega = 0.75$	$\omega = 1$
	$\sigma = 0.75$	$\sigma = 1$	$\sigma = 0.25$	$\sigma = 0.25$	$\sigma = 0.75$	$\sigma = 1$	$\sigma = 0.25$	$\sigma = 0.25$
$\Delta\hat{u}$	-0.9	-0.94	-1.01	-1.07	-2.05	-2.08	-2.17	-2.25
$\Delta\hat{q}_A$	-0.15	1.29	1.27	1.91	-1.94	-1.76	-1.86	-1.82
$\Delta\hat{q}_B$	-1.09	-1.51	-1.59	-1.82	-2.11	-2.26	-2.35	-2.49
$\Delta\hat{e}_A$	-2.68	-1.25	-1.83	-1.49	-1.30	-0.95	-1.80	-2.13
$\Delta\hat{e}_B$	0.12	-0.32	-1.00	-1.55	-0.80	-0.78	-1.61	-2.12
$\Delta\hat{k}_A$	-4.01	-2.56	-2.48	-1.79	-2.79	-2.63	-2.64	-2.56
$\Delta\hat{k}_B$	-1.21	-1.63	-1.65	-1.85	-2.29	-2.46	-2.45	-2.54
$\Delta\hat{E}$	-0.89	-0.66	-1.30	-1.52	-0.99	-0.84	-1.68	-2.12
$\Delta\hat{K}$	-1.84	-1.84	-1.84	-1.84	-2.55	-2.55	-2.55	-2.55
$\Delta\hat{p}_A$	-3.93	-3.85	-4.05	-3.84	-0.91	-0.88	-1.05	-0.88
$\Delta\hat{p}_B$	-0.16	-0.12	-0.24	-0.11	-0.24	-0.20	-0.40	-0.20
$\Delta\hat{p}^E$	-1.77	-1.31	-2.60	-1.22	-1.99	-1.68	-3.37	-1.70

Table 5 summarizes the changes from the baseline equilibrium induced by energy efficiency investment in the target sectors. Our representative policy is a 50% increase in aggregate technology-specific capital.[7] The economy's responses are shown for two scenarios for the productivity elasticity, in Panel A the hurdle values specified in eq. (26) as a function of the parameters, and in Panel B the values of ξ implied by Timilsina et al's (2017) bottom-up calculations. A key result of this numerical exercise is

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[7] Although not an exact analogue because of our aggregation procedure, this policy shock is similar to the increase in technology specific capital costs experienced by Armenia in 2023 and Georgia in 2034 under Timilsina et al's (2016) scenarios.

the values of $\xi^{\dagger}$ in Panel A, which demonstrate that efficiency investments have to be highly productive to avoid incurring a welfare loss: for Armenia (Georgia), $\xi^{\dagger}$ lies in the range 0.99-1.15 (0.95-1.31).

Under these conditions, the variables whose change from the BAU are most sensitive to investment are the inputs of energy and jelly capital to the target sector, as well as the target sector's output price, all of whose responses are negative. The sole variable whose change is consistently positive is the output of the target sector. This effect is smaller in Georgia, a consequence of the reduced efficacy of the benefit channel due to the fact that $\vartheta < \lambda$. Over a broad range of parameter values both sectors' use of energy declines, with the elasticity of abatement in the target sector being twice as large as in the rest of the economy. Energy- and emission leakage is positive when the elasticity of substitution between consumption of the sectors' outputs is small, and negative otherwise (cf Baylis et al, 2014).

The patterns of responses in Panel B differ in many respects. Most consequential is the magnitude of the empirically-derived productivity elasticities, one-tenth to one-half as large as those in Panel A. Not surprisingly, energy efficiency mandates end up reducing welfare, by 0.9-2.3%. The lower productivity of energy efficiency investments are associated with a smaller expansion of the target sector's output, with declines for small values of the consumption elasticity of substitution in Armenia, and for all values of the parameters in Georgia. Symmetrically, the decline in the target sector's output price is considerably smaller. As $\omega \to 1$ the responses of the remaining variables are similar to those in Panel A, while for small values of this elasticity the response of the target sector's energy use and abatement is half as large.

Lastly, comparison of Tables 4 and 5 reveals that the representative policy above is not stringent enough to stabilize energy use and emissions. Evaluating eq. (36) using the parameterizations in Tables 3 and 5 reveals that achieving such abatement necessitates increases in technology-specific capital of 75-90% in Armenia and 73-75% in Georgia.[8] The upshot is severe adverse growth consequences: although the rate of change of utility remains positive in both economies, relative to Table 3 it declines by half in Armenia (1.3-1.8%) and more than four fifths in Georgia (0.4-0.9%). The magnitude of these welfare losses is unsurprising when one considers that the policy attempts to curtail the entire economy's expansion in energy use by increasing efficiency in the commercial and residential sectors that account for 16% and 11% of total consumption. Given the potential for abundant low-cost emission reductions industry, electric power and transportation, our result begs the question whether substantial emission reductions might not be more cost-effectively achieved using policies that incentivize abatement across a broader range of sectors—e.g., an economy-wide carbon tax. The answer awaits future research.

4. Discussion and Conclusions

In this chapter we have developed a conceptual framework connect bottom-up engineering and top-down macroeconomic analyses of the economic and environmental effects of technology strategies to improve energy efficiency while preserving economic growth. Our simple innovation is to utilize raw data from the technology penetration scenarios that underlie the construction of MAC curves to recast technology policies as the substitution of more costly capital input for energy and emissions. Bottom-up MAC curves almost always feature apparent negative total cost technology options for which increases in direct cost associated with inputs of capital are outweighed by reductions in cost associated with savings on inputs of energy. Summarizing the dynamics of the penetration of multiple technologies using capital-energy substitution elasticities enables us to forge connections between attempts to increase technology-specific capital and economy-wide opportunity costs—which arise from reallocation

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[8] The latter figure is 50% larger than the increase in Georgia's technology-specific assumed by the scenarios in Timilsina et al (2017), casting doubt on whether it is even feasible to rely on residential and commercial technologies to achieve emissions stabilization.

of productive capital to increasing energy efficiency, and between the resulting energy savings and aggregate environmental benefits—which are moderated by leakage of energy and emissions from the sectors targeted by policies to the rest of the economy. We demonstrate how an accounting for these two components can be transparently accomplished in the context of a highly stylized two-sector analytical general equilibrium model, both theoretically, and empirically using numerical parameterizations for Armenia and Georgia.

Our numerical results provide a novel recounting of the cautionary tale told by numerous economists: if exogenously imposed energy efficiency regulations mandate investment in technology options that are more costly and/or generate output less productively than the capital that firms themselves would choose, then regulations' macroeconomic costs can be large and their environmental benefits small, even if the targeted sectors are shielded from the direct burden of the additional cost of these investments. The broader contribution of this research is a methodology for combining the results of stage (i) analyses with a simplified model to quickly generate policy-relevant insights capable of improving the design—or, at a minimum, avoiding the major pitfalls—of technology deployment policies. The opportunity costs that are central to our results emphasize that the win-win situation where GHG mitigation increases economic growth is unlikely unless the targeted energy-efficiency investments are highly productive. Nevertheless, our case studies do reveal options where additional capital expenditure can lead to substantial energy savings, and, by extension, output growth in the sectors in which they might be deployed. Our methodology can thus help to focus policy makers' attention on identifying such alternatives, and properly quantifying their broader costs and benefits.

Notwithstanding this contribution, there are numerous gaps in our analysis that would seem to be productive avenues for future inquiry. First, our focus on the engineering and macroeconomic aspects of technology strategies gives short shrift to the behavioral origins of investment inefficiencies. In particular, our presumption that such policies actually remedy the problem they are designed to solve glosses over the fundamental question of what precisely that problem is, in other words, what are the forces constraining wider adoption of the kinds of productive technologies we identify. There are many possible culprits: incomplete information, inattention, heuristic decision making, cash-in-advance constraints or lack of complementary know-how necessary to operate technologies, whose relative importance we are only now beginning to make sense of empirically (Gerarden et al, 2017), and whose operation in poor countries is ripe for investigation. We take pains to emphasize the link to a deeper sustainable development question: do private actors in developing nations systematically overlook, or face barriers to adopting, technologies that are capable of improving their productivity, and in turn increasing the rate of growth of the economy? An affirmative answer would suggest that green growth policies should stimulate adoption of not only technologies that solely conserve energy, but also those that enhance general productivity as well![9] We are not aware of stage (i) studies that explicitly identify technology options that do double duty in this regard; research to do so will likely see productive collaborations between engineers and economists.

The tension between economy-growing and emission-saving innovation in delineating the slate of technologies to be considered points to additional opportunities of research. The lynchpin of our approach is the trick of transforming stage (i) results into a reduced-form static innovation possibility frontier (IPF) that can be easily inserted into stage (iii) analyses. However, our method continues to rely on scenarios of technology penetration that underlie MAC curves' construction, leapfrogging stage (ii) analyses. Different technologies will compete with one another, and this process will both induce and be shaped by the types of economy-wide general equilibrium feedback effects that give rise to the opportunity costs we have shown to be important. It is therefore important to characterize the equilibrium of the adoption process—which technologies end up being used, in what capacities, by

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[9] See, e.g., Parente and Prescott (1994), Syverson (2011), Santacreu (2015), Goni and Maloney (2017).

different actors, as that determines whether policies achieve their intended effect of making the economy's aggregate MAC curve more elastic (less convex), and/or shifting it downward. Di Maria and Smulders (2017) caution that we may get the opposite result if technology is complementary with physical capital that requires polluting inputs to operate, or in economies with additional uncorrected distortions, such that a marginal tightening of environmental policy increases the marginal cost of cutting pollution and reduces abatement. This possibility raises uncomfortable questions about our results for Georgia. Would the assumed penetration of low productivity options actually occur once private actors and policy makers gain experience with and awareness of technologies' performance and costs? If not, how would the equilibrium technology penetration vector differ, and with it the associated implicit elasticity of capital-energy substitution?

The underlying concern is that the ex-ante IPF may itself be endogenous, over and above the ex-post general equilibrium influences revealed by eq. (31).[10] Acknowledging this possibility requires elaborating technology strategies' consequences in a framework that consistently integrates stages (i), (ii) and (iii) to capture the intertemporal feedback on incentives to invest in options that embody varying degrees of pollution-saving and output-expanding innovation. The latter is the strength of models of environmentally directed technical change (DTC). Different from our focus on technology adoption, key papers in this area investigate how a fixed pool of innovatory resources is reallocated between clean and dirty production activities in response to the economy-wide stimulus of a pollution tax or the threat of a pollution-driven environmental disaster (Acemoglu et al, 2012; Fried, 2018). Similar to our model, opportunity costs arise from diversion of resources that would otherwise be employed to increase productivity, output and long-run consumption. Yet the resources themselves are of a very different character—a continuum of generic sector-specific intermediate goods ("machines") with embodied productivity that is increased by allocating more scientific labor or R&D expenditure to the encompassing sector. Moreover, energy is not treated a resource input, but an output that is created from labor and machines. The implication is that we need a new generation of DTC models capable of characterizing the tradeoff between energy saving and reductions in discounted utility for different levels of subsidy to green energy technology options in targeted subset of producing sectors.

Specifying a tractable DTC model that resolves both targeted and non-targeted energy-using sectors as well as energy-saving and productivity-increasing intermediate machines, is a tall order. Some progress has been made: Bretschger et al's (2011; 2017) endogenous technical change CGE model resolves multiple sectors whose productivity is driven by inputs of intermediate machines, which in turn are modeled as demanding labor and a composite of different energy commodities. But because the model aggregates machines in each sector into a broad capital composite, technical change is directed from one sector to another, as opposed to between energy-saving and generally productive varieties of innovation within sectors, ruling out the kind of IPF in which we are interested. The key research need is therefore to further adapt such DTC formulations to specify heterogeneous sectoral capital formulations that are at least minimally congruent with the physical realities of discrete energy-using technology options. Working toward this goal from the opposite direction, Sue Wing and Timilsina (2016) develop a procedure to incorporate bottom-up technologies into individual sectors within a recursive dynamic CGE framework—but assuming a static IPF. The prospects for reconciling these approaches will depend on the development of novel calibration approaches that successfully combine engineering and economic conceptions of technologies and the innovations that improve their performance.

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[10] Following section 2.3, given the program, $\min_{\tilde{x}_{\theta,t},\tilde{x}^*_{\theta,t}}\left\{\sum_\theta \tilde{\mathcal{C}}_\theta \middle| (1)-(5),(14),(16),(17)\right\}$, the questions are how general equilibrium effects on prices and primal boundary variables shift the constraints, and how those in turn influence the optimum and the associated values of ξ_θ and $\bar{\xi}$. While we are not aware of research that has sought to address these questions, we note that linked bottom-up/top-down modeling frameworks (Böhringer and Rutherford, 2009) are well placed to do so.

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