Macroeconomic Consistency Issues in E3 Modeling: The Continued Fable of the Elephant and the Rabbit

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Starting from a short presentation of the limits of using conventional production functions to hybridize energy-economy relationships, this paper presents a methodology aiming at a better integration of bottom-up policy scenarios in a top-down static general equilibrium framework. Along the lines of Ahmad's innovation possibility curve, the methodology consists in implementing top-down envelopes of production and demand functions, whose variable point elasticities of substitution provide a flexible interface for calibration on any bottom-up expertise. Numerical experiments assessing the impact of a rising carbon tax on the global 2030 economy compare the application of this methodology to that of two standard CES-based approaches. Results confirm that, in case of large departures from reference scenarios or of strong convexities in bottom-up results, the use of conventional CES production and utility functions may lead to a significant bias in cost assessment.

1. INTRODUCTION

This paper starts from a paradox in current efforts directed at hybridizing bottom-up (BU) and top-down (TD) analysis of energy-economy-environment (E3) linkages: while the challenge is to benefit from the technology-rich information of BU models when analyzing the macroeconomic implications of public policies, these efforts devote little attention to the consistency between technical change in the energy sector and overall technical change. Instead, they focus primarily on the gap between the engineer's and the economist's descriptions of energy technologies.

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Such a practice is legitimated by the ‘Elephant and Rabbit stew’ metaphor of energy-economy interactions: if the stew “contains just one rabbit (the energy sector) and one elephant (the rest of the economy), won’t it still taste very much like elephant stew?” (Hogan and Manne, 1977). Given the small weight of the energy sector in the economy, this metaphor justifies keeping constant the non-energy production functions of E3 models. However, if it is undoubtedly applicable when small departures from reference trends are considered, it becomes more debatable when drastic modifications of these trends are required by ambitious long-term objectives such as decarbonization.

This paper scrutinizes the terms and significance of this issue. The first section stresses the importance of adopting an endogenous technical change framework to discuss it. The second presents a methodology for defining static production and utility functions whose coefficients vary in consistency with energy systems information at a given time horizon. A third section compares the numerical results of this methodology to that of two contrasted TD modeling approaches, to demonstrate its importance in the case of large policy-induced departures from reference projections.

2. BACK TO THE CRUX OF THE MATTER: PRODUCTION FUNCTIONS

One almost perfect illustration of the “elephant and rabbit” metaphor, in a very aggregate form of TD analysis, is MARKAL-MACRO (Hamilton et al., 1992): MARKAL minimizes the discounted sum of energy costs while MACRO maximizes the discounted sum of the utility of consumption. The link between the two models is made through MACRO’s CES production function of its unique consumption good, which trades off a composite factor KL (aggregated through a Cobb-Douglas function) and MARKAL’s 23 energy services to households and firms, while energy costs are subtracted from total output. However, the CES coefficients are constant whatever the time period and the stringency of constraints on the energy system—which amounts to assuming constancy of the macroeconomic growth engine.

Less aggregated models proceed in the same way: Böhringer (1998) demonstrates that substituting six engineering-based Leontief descriptions of electricity generation to a single CES approximation significantly impacts policy analysis, but he does so with a constant capital stock and unchanged production functions of non energy goods. McFarland et al. (2004) also focus on electricity generation, stressing that constant substitution elasticities entail the risk of violating the necessary limits to the performance of a technology at a given point in time—together with, ultimately, thermodynamic laws. They develop a carefully crafted nesting structure of inputs to electricity production, but again do not change the other production or utility functions.

A first issue overlooked by these endeavors is that BU analysis provides information under a *cœteris paribus clausa*: it considers the impacts of energy price (and non-price) signals on the energy system, but not on the rest of the economy. It thus ignores impacts on (*i*) the prices of non energy goods (through the input-output structure); (*ii*) the labor costs (through the interplay between the purchasing power of wages and the functioning of the labor markets); (*iii*) the capital costs (through changes of the savings rate and in the cost of equipment); (*iv*) the exchange rates. Eventually, a carbon tax in a BU model is only nominal, while it leads to a different signal, in real terms, after general equilibrium adjustments. What ultimately matters is that the relationships between technical choices and relative prices after general equilibrium adjustments be consistent with those described by BU analysis. The challenge is to avoid describing a Chimera economy by hybridizing BU and TD models which do not depict the same world.

A second issue is the legitimacy of the elephant and rabbit metaphor, given the possible chain of impacts of drastic changes in the energy sector on the very structure of the economy. Various examples of such interplays can be given, such as the impact of abundant domestic resources on the structure of the US steel industry if compared with Europe and Japan (Wright, 1990), or the consequences of the choice of nuclear energy, and the following electrification of industrial processes, on the French industrial structure in the seventies and eighties (Hourcade and Puiseux, 1986).

Capturing the modifications to the macroeconomic growth engine that might be induced by drastic changes in the energy sector is obviously impossible keeping constant households' utility functions, autonomous energy efficiency indexes (AEEI)[1] and the substitution between capital, labor and non-energy intermediate consumption in non energy sectors. Understanding the underlying methodological issues demands a brief theoretical detour.

Since Berndt and Wood (1975) and Jorgenson (e.g. Jorgenson and Fraumeni, 1981), KLE or KLEM production functions are assumed to mimic the choices of techniques and the technical constraints impinging upon an economy. But, from the outset, an ambiguity pervades the use of this way of expanding to energy and other intermediary inputs the method employed by Solow in his growth model, *i.e.* the calibration of a hypothetical production function on observed cost shares, interpreted as an economic equilibrium. Solow himself warned (1988, p. 313) that "this 'wrinkle' is acceptable only at an aggregate level (for specific purposes) and implies that we should be cautious about the interpretation of the macroeconomic production functions as referring to a specific technical content".

To neglect this warning leads to mix up the economic productivity of investments and the technical efficiency of equipment, a confusion that fuelled the

1. AEEI indexes account for all the indirect sources of decoupling between energy and output; these sources (R&D, energy efficiency standards, structural changes, etc.) cannot but be impacted by large-scale shifts in energy trends.

Cambridge controversy from the fifties up to the early seventies.[2] Nonetheless, the inclination to interpret production functions as sets of actual techniques gained more ground as computational progress allowed for more disaggregated models. Whatever the level of disaggregation, though, these functions remain calibrated on cost-share data: they convert money-metric information into physical terms through Shepard's lemma, which holds only if, at each point in time, economic data can be interpreted as the optimal response to a price vector.[3] Frondel and Schmidt (2002), analyzing several hundreds of econometric estimates of capital-energy substitution elasticities, emphasize the constraints due to the mathematical properties of the functional forms. They conclude that "inferences obtained from previous empirical analyses appear to be largely an artifact of cost shares and have little to do with statistical inference about technology relationships" (Frondel and Schmidt, 2002, p.72).

Even if one does not derive dramatic conclusions from such a pessimistic assessment, the point remains that translating cost shares into technical constraints is valid only at the neighborhood of an optimal equilibrium—which makes it difficult to address debates about the efficiency-gap (Jaffe and Stavins, 1994), hysteresis effects leading to multiple technological equilibria (Gritsevskyi and Nakicenovic, 2002), or any large departure from reference trends.

This discussion could be argued to be purely rhetorical, either because the distortions induced by modeling artifacts are not significant, or because there is no conceivable better alternative. The question is: if a given partial equilibrium analysis contains some piece of truth, in what way should and could it be used to inform our vision of the corresponding growth engines? Economists addressing this question are forced to accept their predictions to be conditional upon useful but often controversial engineering-based prognoses about future energy systems. Their contribution is to reveal with what plausible assumptions about the future economy these prognoses are compatible. Fulfilling this ambition implies two prerequisites.

The first is to have a description of the economy explicitly in prices and in physical quantities, which does not rely on functional forms with constant coefficients whatever the level of departure from reference trends. It is indeed unlikely that the elasticity of substitution between capital, labor and energy at a $10/tC carbon price remains valid at a $500/tC carbon price. This is true for any specific industry, but also in aggregate production and demand functions because structural transformations of the economy induced by energy policies at some fixed

2. This controversy was about the 're-switching' problem in technical choices and was conducted in the most influential economic journals. Even though it started from a question about the very status of capital in growth theory, it polarized, perhaps mistakenly, around distributional issues, i.e. the remuneration of capital and labor (Cohen and Harcourt, 2003).

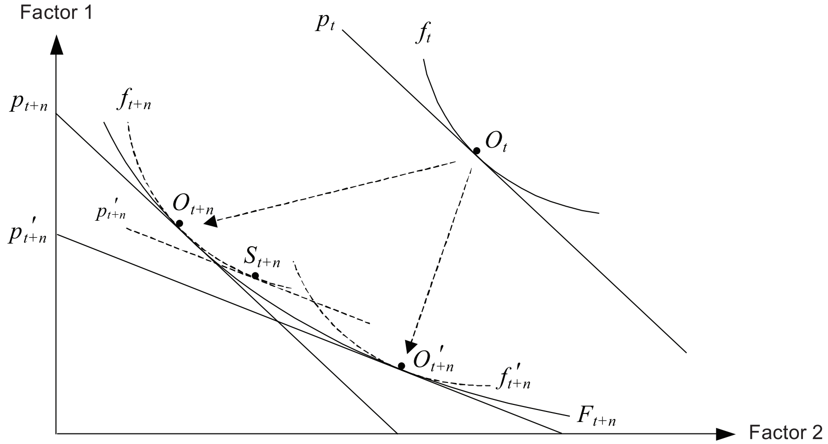
3. Another caveat by Solow was: "[...] total-factor-productivity calculations require not only that market prices can serve as a rough-and-ready approximation of marginal products, but that aggregation does not hopelessly distort these relationships [...] over-interpretation is the endemic econometric vice." (Solow, 1988, p. 314)

horizon also become difficult when substitution possibilities vanish on both the demand and supply side.

The second is to work under an endogenous growth framework. First, this is consistent with postulating that induced technical change in the energy field modifies the growth engine. Second, it allows for making a clear distinction between substitutions along a given production frontier at a given point in time, and the induction of new frontiers by various historical sequences of relative prices.[4] As noted by Ruttan (2002), this traces back to Hicks: "A change in the relative prices of the factors of production is itself a spur to invention and to inventions of a particular kind—directed at economizing the use of a factor which has become relatively expensive" (Hicks, 1932, p. 124).

Figure 1, adapted from Ruttan (2002), illustrates this point: it pictures production techniques as combinations of two factors along unitary isoquants. The isoquant f_t describes the available set of factor combinations at time t, from which the relative prices p_t imply selecting O_t. At time $t+n$, assuming some technical change and constant relative prices $p_{t+n} = p_t$, the optimal factor combination will have shifted from O_t to O_{t+n}, on a new f_{t+n} isoquant. Now, if the historical sequence of relative prices leads to p'_{t+n} instead, the economy should generate f'_{t+n} rather than f_{t+n}, and the new optimum would be O'_{t+n}. Exploring from date t the range of possible $t+n$ relative prices reveals what Ahmad (1966) called an "innovation-possibility curve", *i.e.* an envelope F_{t+n} of the possible production functions f_{t+n}. At $t+n$, along a given envelope the functions f mutually exclude one another: if the reference scenario leads to f_{t+n}, an instantaneous shock in relative prices will shift the choice of technique to S_{t+n} rather than O'_{t+n}, since f'_{t+n} is no longer an available option.

Figure 1. Induced Technical Change as a Dynamic Production Frontier



4. An improvement over the paradox of empirical work on the static production function—which, to be econometrically valid, are forced to calibrate over data covering several decades that cannot have failed to induce quite different production frontiers.

3. METHODOLOGY FOR A STRUCTURED DIALOGUE

The methodology proposed hereafter applies the notion of an innovation possibility curve to carbon pricing: over the long run, any sequence of price signals induces a specific production frontier, together with a specific households' energy demand function through changes in end-use appliances or equipment. It builds on BU information to conduct a comparative-static analysis of two equilibria, situated at some *t+n* horizon, on two stabilized growth pathways generated by two different sequences of carbon price signals between *t* and *t+n*. The underlying vision of technological dynamics is that each investment vintage embodies technical change[5] and that the static production and demand functions at a given date result from past vintages. This echoes Thomsen's recommendation to use a short run function stripped down from a long run cost function (Thomsen, 2000).

The comparative-static analysis starts with ensuring that BU and TD no-policy projections portray the same world at the selected *t+n* horizon. This implies constructing the value and quantity macroeconomic balances consistent with the baseline BU projection of the energy sector. Then, the revelation of the time *t+n* envelopes of production and demand functions consistent with BU expertise is conducted for a range of carbon prices wide enough to capture the asymptotic behavior of energy systems. This revelation is made possible by interpreting the results of BU policy simulations as the partial price derivatives of the unknown static production and demand functions generated by the corresponding sequence of price signals. The last step is to integrate the effect of energy supply and demand capital requirements on total factor productivity.

3.1. Value and Quantity Balances in the No-Policy Projection

Any BU projection of an energy baseline is necessarily consistent with some GDP level and energy prices. It also contains other information that can be used to define some constraints impinging upon the underlying no-policy economy, but part of the necessary information is missing to develop a consistent picture of this economy.

Let us start from the price/quantity decomposition of national accounts of a global economy with two goods, energy E and the remainder of economic activity Q: in Table 1, E and Q (in rows) are used in intermediate consumption (IC) households consumption (H) and Gross Fixed Capital Formation (GFCF, nil for energy); the inputs for the production of E and Q (in columns) include, in addition to IC, labor (L) and capital (K) expenditures.[6]

5. The 'technical' change in an aggregate description of production obviously incorporates changes in the composition of the output; capital turnover in part governs the pace of this transformation.

6. For clarity's sake, our presentation does not detail the treatment of taxes and the correlated public expenditures. Section 3 will describe which assumptions were made in this regard in the numerical runs.

Table 1. Price/Quantity Decomposition of an Aggregated Accounting Table

IC		Q	E	T	H	GFCF	'Uses'
	Q	$p_Q \alpha_{QQ} Q$	$p_Q \alpha_{QE} E$	Σ	$p_Q Q_c$	$p_Q Q_k$	$p_Q Q$
	E	$p_E \alpha_{EQ} Q$	$p_E \alpha_{EE} E$	Σ	$p_E E_c$	-	$p_E E$
	T	Σ	Σ	Σ (IC)	Σ	Σ	Σ
VA	L	$w\, l_Q Q$	$w\, l_E E$	Σ			
	K	$r\, k_Q Q$	$r\, k_E E$	Σ			
	T	Σ	Σ	Σ (GDP)			
'Resources'		$p_Q Q$	$p_E E$	Σ			

Subject to harmonization between the BU and macroeconomic accounting of energy and financial flows, BU analysis provides explicit information on:

- total energy production (E),
- the energy intensity of energy production (α_{EE}),
- households' aggregate energy consumption (E_c),
- an average price of energy p_E.[7]

Adopting the composite good as numéraire, and setting its price to 1,[8] a vector of 12 unknowns (w, r, α_{QQ}, α_{EQ}, α_{QE}, l_Q, l_E, k_Q, k_E, Q, Q_c, Q_k) remains to represent an economy compatible with the no-policy BU projection. The number of unknowns can be reduced by imposing the GDP and intermediate energy consumption $\alpha_{EQ}\, Q$ of the BU projection. Flow balances provide four additional constraints (one per good in both monetary and physical terms). Six unknowns thus remain, not provided by BU data.

To use Solow's "wrinkle" solves this problem by assuming that: (*i*) the production of e.g. Q is a function f_Q, valid between t and $t+n$, of real consumption of good Q, E, labor ($l_Q\, Q$) and capital ($k_Q\, Q$), and of a given autonomous technical change; (*ii*) these factors are substitutable, and their equilibrium demands determined by minimizing the production costs for the price vector (p_Q, p_E, w, r). Under these assumptions, calibrating production and utility functions on the national accounts at some base year t[9] and on the energy systems at t and $t+n$ suffices to recompose $t+n$ national accounts consistent with the BU no-policy projection.[10]

However, this results in a stand-alone tool, which simultaneously solves

7. p_E is obviously differentiated among energy uses because of taxes and subsidies. We do not emphasize these differences here.

8. This is equivalent to using the monetary values as the quantity measure of good Q, without loss of generality.

9. Starting from national accounts, a price-quantity decomposition supporting this calibration is conventionally made setting $p_Q = p_E = w = 1$ and deriving the price of capital and the capital contents k_Q and k_E from a measure of $p_Q\, K$ the value of the stock of productive capital, letting $K = k_Q\, Q + k_E\, E$.

10. With the conventional production functions the system even needs additional degrees of freedom in the form of exogenous trends of biased technical change.

the no-policy economy, and its reactions to energy policies without further reference to BU expertise. This tool thus ignores how (*i*) the t+n partial price derivatives estimated by BU analysis vary with the sequence of price vectors between t and t+n, and (*ii*) changes in f_E, the production function of energy may impact f_Q. However, this difficulty can be turned into an advantage: it justifies revealing sequentially the BU-compatible no-policy TD projection, and the behavioral equations capturing the responses at t+n to policy signals between t and t+n.

Returning to the six remaining unknowns above, two can be found by setting labor and capital prices to 1. Moreover, aggregate labor and capital costs of energy production can be derived from the comparison of fixed and variable costs usually incorporated in BU models. Finally, two more constraints can be econometrically set or chosen by judgment (subject to appropriate sensitivity tests): the savings rate and the share of labor expenditures in the value-added of the composite good. It now remains to define for this baseline economy some behavioral equations compatible with the BU policy simulations.

3.1. Envelope of the Energy Production Functions

For the sake of simplicity, we consider that policies only alter the energy and capital intensities of the energy good, and we keep constant its labor and material intensities between the no-policy and policy cases.[11] BU analyses generally provide sets of matching relative variations in factor intensities (α_{EE}, k_E) and prices (p_E, r) over a range of carbon prices—implicitly assuming all non-energy BU prices constant, including r. Relative variations of α_{EE} and p_E are directly computed, while those of k_E can be equated to those of the capital stock per physical unit of energy produced. The resulting data set is used to calibrate α_{EE} and k_E as functions of the ratio of their prices, through the least-square adjustment of an arctangent specification (selected to allow the reproduction of any asymptote to substitution possibilities).

A non-negligible difficulty regards the consistency between capital costs as they appear in national accounts, and the investment in energy production as reported by energy models. In Table 1, $r\, k_E\, E$ is a remainder of value-added (VA), once labor costs are subtracted, that encompasses not only equipment expenditures, but elements as heterogeneous as interest payments, rents (on land, water, mineral and fossil resources) and a mark-up depending on market characteristics. The credibility of a hybridizing exercise using it as an index of productive equipment is questionable, all the more so as capital costs in energy production are key in policy assessments. This difficulty can be surmounted by distinguishing, in the

11. The non-energy variable costs of E reported by BU expertise provide an estimate of the sum of material and labor costs. The labor content of energy production is low and its variation as a function of policy signals can be neglected at a macroeconomic level. Changes in the non-energy intermediate consumption embodied in new techniques may be more significant; should such information be delivered by BU analysis (it is not in the current state of the art), it could be easily inserted in the proposed methodology.

non-labor VA, genuine equipment expenditures, calibrated on total GFCF data net of investment in housing,[12,13] and the corresponding interest payments, estimated on a limited set of exogenous assumptions: an average capital lifespan and a real interest rate.[14]

3.2. Envelope of the Composite Good Production Functions

Contrary to the case of energy production, the labor content of composite production has a paramount influence on cost assessment. A set of functions f_Q must thus be revealed, to produce the labor content, and as a matter of fact the capital content, necessary for the calibration of the envelope of these functions. This is done based on the following assumptions:

- All policy-induced time $t+n$ economies are on a steady equilibrium path, guaranteeing to each f_Q the first-order conditions of relative marginal productivities equating relative prices (for any two production factors).
- For a given output and around a given energy price p_E, the price elasticity of energy demand is derived from BU analysis considering a marginal increase of p_E.

For a selected functional form, there is a single f_Q making these assumptions compatible with the no-policy price and factor-demand vectors. The same mathematical property can be applied successively to every pair of equilibria separated by a marginal increase of the energy price.

Let us assume, given their wide usage in the E3 modeling community,[15] that CES functions of capital K_Q, labor L_Q and energy E_Q approximate each real f_Q at the neighborhood of the corresponding equilibrium. A unique CES of the no-policy projection, CES_0, can be calibrated imposing (*i*) the linear homogeneity condition, (*ii*) the first-order conditions at the no-policy equilibrium and (*iii*) the energy demand E_{Q1} resulting from a marginally higher energy price under constant other prices and output, as computed by BU expertise. CES_0 then provides the optimal K_{Q1} and L_{Q1} prevailing under the new price regime. The same method is applied using the newly defined (K_{Q1}, L_{Q1}, E_{Q1}) equilibrium, and the impact of a further marginal energy price increase in the BU analysis. This allows the successive identification of equilibrium (K_i, L_i) compatible with the BU information on

12. Note that in the conventional price and quantity decomposition, GFCF data is disconnected from the capital intensities of production. The link exists in dynamic analysis through the equation of capital stock formation; it is lacking in many static analyses, where the capital stock K is usually kept constant through ad hoc adjustments of *r*.

13. Government investment is not a problem here: in national accounts it appears as the investment of a sector exclusively devoted to the production of one aggregate public good—the only good consumed by government. In Table 1's aggregated framework government investment is thus part of $r\, k_Q\, Q$.

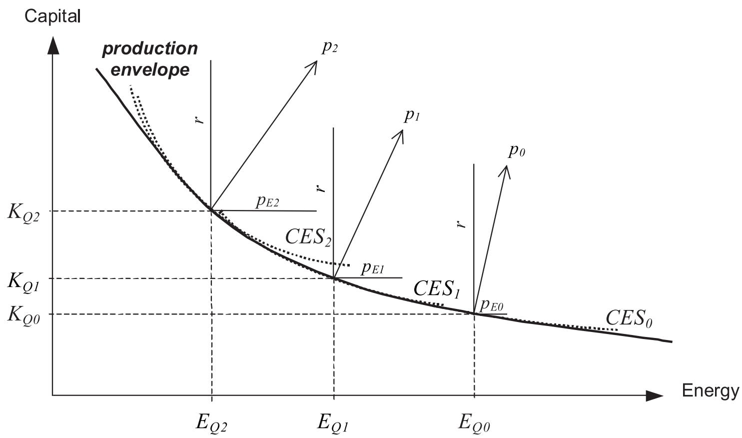
14. Interest payments are a percentage of equipment expenditures, easily computed by setting an average lifespan of capital, and a constant rate of growth of equipment expenditures together with a constant real interest rate over this lifespan (the two rates are assumed equal on a stabilized growth path).

15. E.g. in models as G-Cubed, MS-MRT, SGM, EPPA. Cf. respectively Mc Kibbin and Wilcoxen (1995), Bernstein et al. (1999), Fisher-Vanden et al. (1993), Babiker et al. (2001).

(p_{Ei}, E_i) couples over the whole spectrum of analysis.

Figure 2 illustrates this method in a two-dimensional E-K space: CES_0 is defined by E_{Q0}, K_{Q0}, the no-policy price vector p_0 and a BU-derived (p_1, E_{Q1}) couple; it defines the optimal K_{Q1} under p_1; CES_1 is then in turn defined by E_{Q1}, K_{Q1}, p_1, and a BU-derived (p_2, E_{Q2}) couple; etc.

Figure 2. Production Envelope of Energy and Capital in the Composite Production



The resulting set of prices (r, w, p_{Ei}) and factor demands (K_i, L_i, E_i) is used to adjust the predefined functional forms of conditional demands of the three factors. This is done at the unitary level of capital, labor and energy intensities, as the substitution elasticities revealed are assumed to hold whatever the eventual production level. Note that, even though a CES function is assumed around each equilibrium, the resulting implicit envelope has no reason to exhibit a constant elasticity of substitution, unless in the implausible case of a constant price elasticity of E_Q over the range of policies explored.

3.1. Households' Savings and Envelope of Demand Functions

The behavior of households at $t+n$ is composed of a savings decision and a trade-off between consumption of energy E_c and Q_c, subject to the income constraint. We assume a constant savings rate applied to the VA net of equipment expenditures. This means a constant ratio of households' expenditures on housing investment—while productive investment matches the equipment expenditure consistent with the production levels of E and Q.

Regarding the energy-composite trade-off, BU analyses do not systematically report on the proper arguments of utility functions, *i.e.* energy services (heating, lighting, passenger-kilometers, *etc.*), whose variations may differ from those of energy consumptions *per se* thanks to efficiency gains. Our methodology consequently focuses on the Marshallian demand functions for E_c, without revealing the underlying set of utility functions.

An envelope of the Marshallian energy demands is calibrated on BU information about households' energy consumptions. This information is first translated in terms of the share of households expenditures devoted to energy, assuming that BU analyses implicitly consider total household expenditures constant;[16] the envelope function is then least-square adjusted to link variations of this share to shifts of the energy and composite price ratio—again, given the constancy of non-energy prices in the BU analysis.

3.2. Feedback on Total Factor Productivity

The impact of carbon constraints on total factor productivity in the composite sector[17] is derived from a comparative-static analysis of an endogenous growth mechanism; it consists in modifying all factor intensities by a Hicks-neutral technical progress coefficient function of cumulated investments. The assumption that all $t+n$ projections are on a steady equilibrium path justifies the use of variations of the $t+n$ equipment expenditures as a proxy of those of cumulated investment.[18]

Under this specification, the crowding-out effect of mobilizing more resources in the production and consumption of energy is not accounted for through the allocation of a fixed capital stock or GFCF. Instead, firms finance their investments (equipment expenditures augmented by interest payments) under the double constraint of market balances—investment goods are produced by the composite sector—and of the ability of households' purchasing power to sustain the resulting price increases. Cumulated investments and the induced productivity of the composite sector consequently align.

4. WHY REVEALING THE INNOVATION-POSSIBILITY CURVES MATTERS

The following numerical experiments consist in the comparative-static assessment of a wide range of carbon taxes on a global two-sector economy in

16. Note that the assumptions of constant expenditures, constant composite consumption, and constant composite price, are incompatible with variations of the energy expenditures. Given necessarily constant non-energy prices, we prefer to consider a constant income (more compatible with the fixed GDP assumption) rather than a constant consumption of the composite good.

17. Because energy models increasingly account for the impacts of learning-by-doing and R&D efforts on the costs of energy technologies, the envelope of energy production functions is assumed to embody such effects.

18. The specification is calibrated so that a doubling of cumulated investment triggers a 20% cost decrease, extrapolating 1978 to 2000 time-series for France and OECD. Further econometrics are needed to extend it to a global estimate, but sensitivity analyses demonstrate that variations of the elasticity of TFP to real investment do not qualitatively affect this paper's conclusions.

2030.[19] Given the purpose of this paper, they do not envisage various recycling schemes for tax revenues, which would necessitate a discussion of issues such as the functioning of labor markets. Instead, they assume full employment and lump-sum recycling, with constant government consumption in real terms.

A first set of simulations uses energy systems information from 60 policy runs by the POLES model (Criqui, 2001), considering a price signal linearly increasing from 0 in the year 2000 to between 37 and 2,241 year-2000 euros per ton of C (hereafter €/tC) in 2030.[20] A second set uses alternative data (ALTER) on energy efficiency, more in line than POLES' econometric treatment of energy demands with the usual outcome of a fully BU analysis: close-to-negative cost options for very low price-signals and an asymptotic saturation of policy impacts at the farther tail of the price spectrum.

POLES and ALTER data are used in general equilibrium analyses resorting to either section 2's envelope methodology (the IMACLIM-S model) or a set of CES functions calibrated by minimizing the least-sum-of-squares of the differences between the BU data and their respective Marshallian demands. The experiment is enriched in the CES case by treating capital as either (*i*) a fixed endowment independent from macroeconomic conditions (following *e.g.* Böhringer, 1998)—hereafter the 'CES Kfix' assumption, or (*ii*) a variable stock of physical equipment produced by the composite sector (cf. 2.2 above) and endogenously affected by the constraints on the energy systems and the changes in the growth pathway—hereafter the 'CES Kvar' assumption. Table 2 synthesizes the differences between these three approaches.

4.1. *Ex ante* Differences in the Calibration of Production and Demand Functions

The ability of each specification to reproduce POLES and ALTER data is assessed by comparing, for an increasing carbon price and all other prices constant, the original data to its envelope- or CES-computed counterpart. IMACLIM-S envelopes fit unsurprisingly well (they are designed to do so), while CES functions misadjust in a proportion that varies with both the sector and the energy data considered. The question is the degree of this maladjustment, and to what extent it has a significant impact on cost assessments.

Starting with households' demand (Fig. 3), POLES results appear 'CES-compatible', while ALTER assumptions are not: for a constant income level, the two ALTER-calibrated CES demand functions underestimate by more than 20% the decrease of households energy consumption triggered by a carbon price be-

19. The 2030 projection is consistent with the no-policy projection of the POLES model following section 2.1 above. The annual global GDP growth rate used by POLES is a conservative 1.73% resulting from detailed projections for 140 countries by a Mankiw, Romer and Weil (1992) model (Kousnetzoff, 2001).

20. A linear tax sequence is a plausible policy decision that limits the risk of hysteresis effects or transitional shocks, and is consistent with the assumption of an economy on a balanced growth path.

Table 2. Main Assumptions Backing Three Comparative-Static Analyses

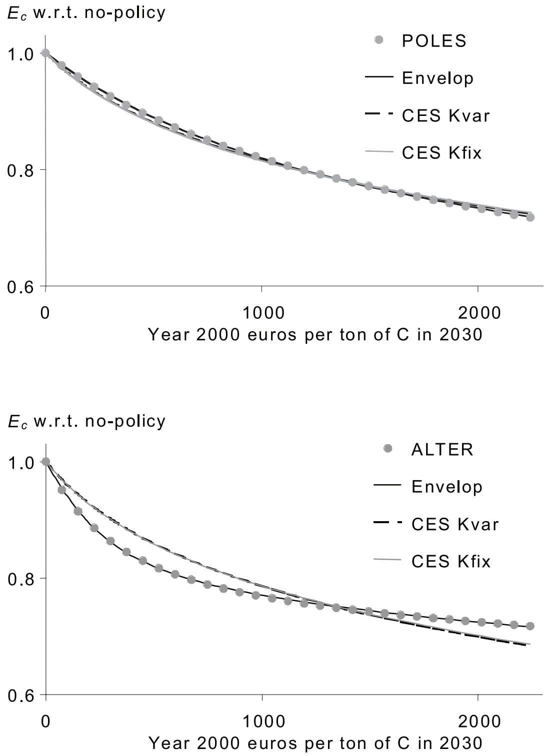
		IMACLIM-S	CES Kvar	CES Kfix
Capital Markets	Interpretation of VA net of *L* costs	Sum of equipment expenditures, interest payments and mark-up (cf. 2.2 above)		Capital services
	K stock	Implicit, variable (fixed proportion of annual productive investment)		Explicit, fixed (endowment)
	K price	p_{Qk} (1+τ), price of composite good for GFCF corrected from interest rate variations (interest rate assumed equal to real growth)		*r*, market-clearing price (varying interest rate)
	Investment	Explicit, variable (fixed share of household revenues + equipment exp. of the two sectors + household abatement investment)		Implicit
Production	Capital intensity of Q, k_Q	f (p_{Qk} (1+τ), p_{EQ}, p_{LQ})	CES (p_{Qk} (1+τ), p_{EQ}, p_{LQ})	CES (r, p_{EQ}, p_{LQ})
	Energy intensity of Q, α_{EQ}	f (p_{Qk} (1+τ), p_{EQ}, p_{LQ})		
	Labor intensity of Q, l_Q	f (p_{Qk} (1+τ), p_{EQ}, p_{LQ})		
	Capital intensity of E, k_E	f (p_{Qk} (1+τ), p_{EE})	CES (p_{Qk} (1+τ), p_{EE})	CES (r, p_{EE})
	Energy intensity of E, α_{EE}	f (p_{Qk} (1+τ), p_{EE})		
Consumption	Household trade-off between composite Q_c and energy E_c	f (p_{Qc}, p_{Ec})	CES (p_{Qc}, p_{Ec})	

tween 0 and 550€/tC. Conversely, for prices higher than 1000€/tC the CES allows for a continuing decrease in consumption that contradicts the saturation effects of ALTER data.

Calibrating the energy sector production proves even more difficult, as not only energy consumptions but also capital intensities are fitted on energy systems data. This causes discrepancies as significant under POLES calibration as under ALTER calibration (Fig. 4): the increase of k_E is overestimated by more than 30% on the whole price range explored, and, simultaneously the fall of α_{EE} underestimated by more than 20% beyond 370€/tC, 30% beyond 450€/tC.

Turning to composite production, all three specifications reproduce POLES' energy intensity (α_{EQ}) variations remarkably well (Fig. 5), but difficulties appear again when calibrating on ALTER: the two CES underestimate α_{EQ} decreases by more than 40% up to 215€/tC, by more than 20% up to 600€/tC and cannot render saturation hypotheses for the higher price signals. Similarly to households' demand, the CES specifications thus offer an acceptable approxima-

Figure 3. Households' Consumption Data and Calibration



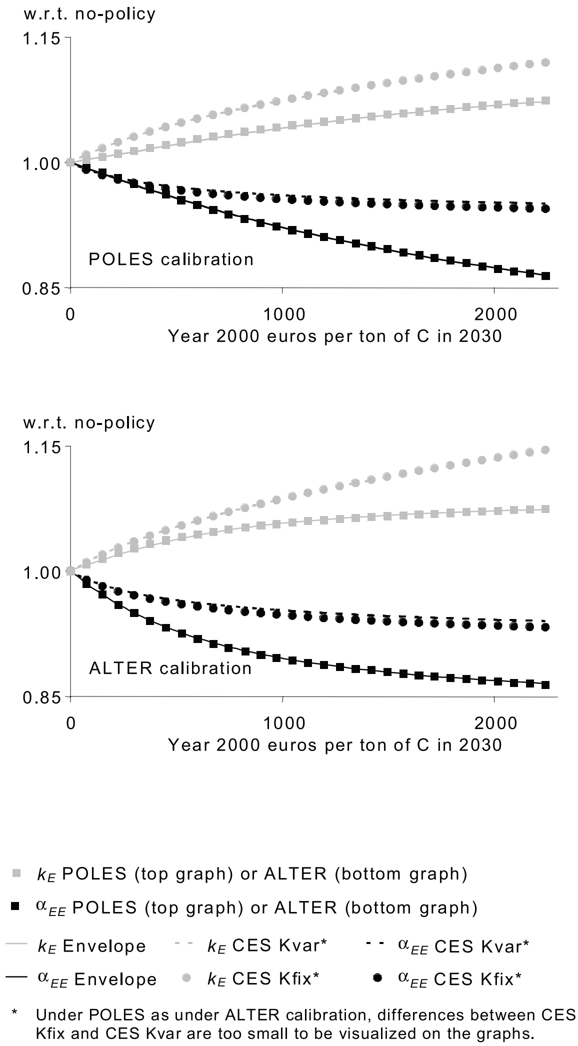
tion of those of the energy systems data which do not exhibit strong convexities in the technical responses to carbon constraints.

Let us now compare the elasticities of the three specifications. Regarding the CES, Table 3 logically shows significantly higher substitution elasticities of production and utility functions if calibrated on ALTER. It also indicates that the assumption on capital does not impact the resulting elasticities: identical functional forms calibrated on similar data produce closely comparable results.

Table 3. Constant Elasticities Resulting from Calibration

		Households' utility	Energy production	Composite production
Under POLES	CES Kvar	0.14	0.09	0.43
	CES Kfix	0.15	0.10	0.42
Under ALTER	CES Kvar	0.18	0.11	0.49
	CES Kfix	0.19	0.12	0.49

Figure 4. Energy Production Data and Calibration



Turning to the envelope, Figure 6 reports the varying point elasticities of substitution of composite production[21] across the range of carbon prices explored. While it varies closely around its constant CES counterparts with POLES data, it dramatically diverges at both ends of the carbon price range explored when calibrated on ALTER.

21. i.e. the substitution elasticities of the series of CES forming the envelope (cf. section 2.3).

Figure 5. Energy Intensity of Composite Production: Data and Calibration

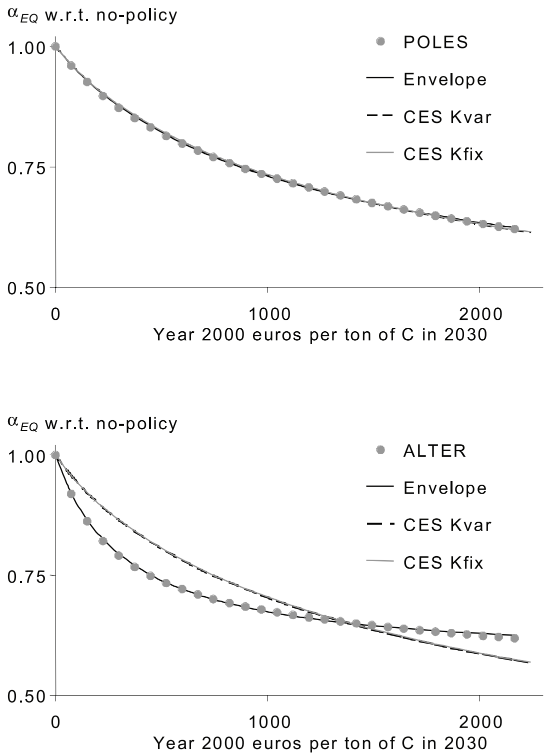
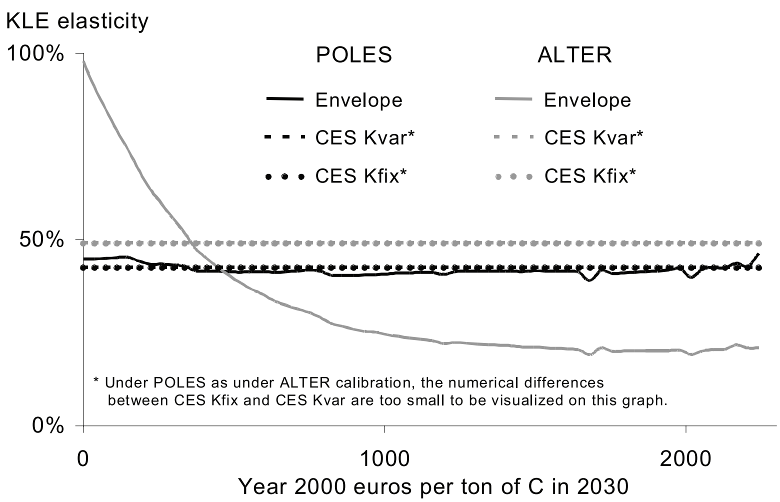


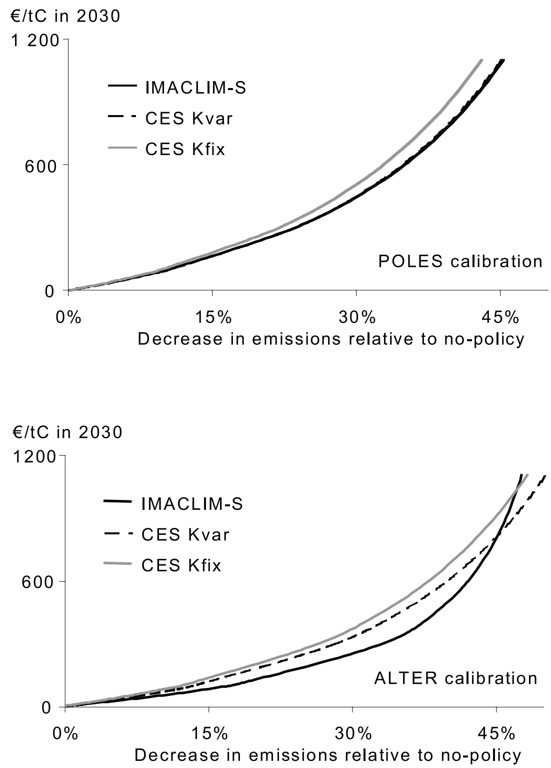
Figure 6. KLE Point Substitution Elasticities in the Composite Production



4.2. Ex post Differences in General Equilibrium Cost Assessment

The first metric to assess the cost of various carbon constraints is the marginal abatement cost (MAC), indicative of the burden to be passed on to the consumer. The MACs estimated with POLES data by IMACLIM-S and both CES approaches do not significantly differ for abatement targets up to a 20% emissions decrease (Fig. 8). Beyond that level, the CES Kfix estimate diverges: for a 40% emissions decrease it is 13 to 14% higher than that of IMACLIM-S or CES Kvar. Since CES Kfix and Kvar share very similar elasticities, this discrepancy must originate in a contrasted evolution of the price vector, caused by a differentiated treatment of capital: in CES Kfix, the capital endowment becomes relatively abundant as economic output declines; consequently, although it faces rising capital intensities, its market-clearing price does not increase as much as the price of equipments does in IMACLIM-S or CES Kvar, where it inflates with p_Q. For a given marginal price, this leads to lower energy price increases and a lesser impact on emissions.

Figure 8. MAC Curves under POLES and ALTER Calibration



Calibrating on ALTER exacerbates the discrepancies between IMACLIM and the CES: up to a 34% emissions decrease, both CES estimates are 40% higher than the IMACLIM-S MAC; for higher abatement levels the gap narrows and dramatically reverses beyond 45%. This result is fully explained by the maladjustments of the CES functions for intermediate and final energy consumption (Fig. 3 and 5) and by their inability to reproduce large low-cost abatement potentials and saturations of technical change.

Turning to macroeconomic costs, POLES' absence of information on energy efficiency in households' consumption and the consecutive lack of an explicit utility function prompts the joint use of two indicators: (*i*) households' composite consumption Q_c (Fig. 9) as a lower bound of welfare losses, assuming stable energy services thanks to efficiency gains fully compensating the decrease in energy consumption; and (*ii*) real GDP (Fig. 10) as an upper bound, under the opposite assumption of nil efficiency gains.

Figure 9. Households' Composite Consumption under POLES and ALTER Calibration

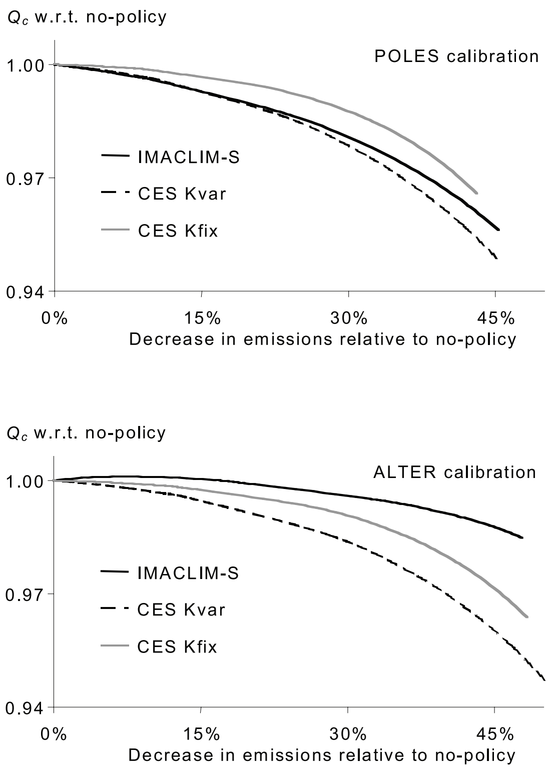
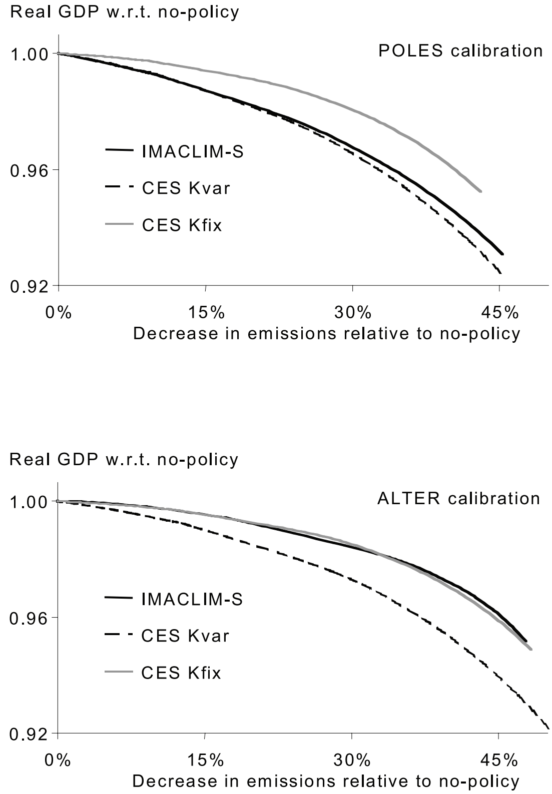


Figure 10. Real GDP Variations under POLES and ALTER Calibration



A first result is that CES Kfix is significantly more optimistic than CES Kvar, whatever the calibration data or the cost indicator considered. This is again explained by the availability, in CES Kfix, of an exogenous capital endowment causing lower price increases. The fixed capital endowment assumption, which is not fully consistent with an endogenous technical change framework, is thus proven to introduce a significant bias in cost assessments. Note that the similarity of IMACLIM-S and CES Kfix estimates for real GDP losses under ALTER assumptions is fortuitous: their households' consumption diverge significantly because households' revenues from capital increase far less in CES Kfix than in IMACLIM-S; but CES Kfix happens to compensate this, in terms of GDP, by higher activity in the energy sector, sustained by its overestimation of energy intensity α_{EE}.

CES Kfix aside, this leaves CES Kvar and IMACLIM-S, with their identical treatment of capital markets, to be compared. There is a strong contrast between their resemblance under POLES calibration and their difference under ALTER calibration.

Under POLES calibration, comparable behavioral functions (cf. 3.1) in an identical macroeconomic framework logically result in comparable cost estimates. Still, aggregate costs are slightly more differentiated than MACs (Fig. 8): CES Kvar computes Q_c losses 7% higher than IMACLIM-S for a 25% target, 10% higher for a 30% target. This increasing discrepancy comes from the biased calibration of energy production in CES Kvar: for the same carbon price, CES Kvar estimates higher energy price increases (Fig. 4), with a stronger impact on households' purchasing power and general economic activity. Note that this bias remains hidden in the MACs: in terms of abatement, the overestimated reduction of economic activity is roughly compensated by the underestimation of α_{EE} decreases.

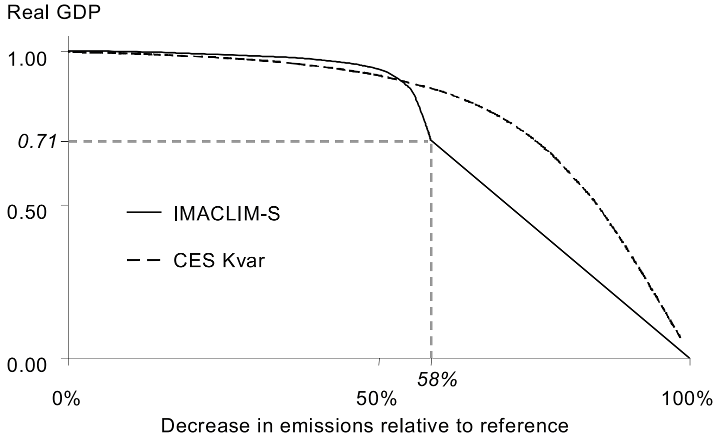
Under ALTER calibration, the divergences are markedly greater, with significantly lower costs for IMACLIM-S (at the minimum, twice as low as CES estimates). This is unsurprising for the lower targets since IMACLIM-S reproduces ALTER's extensive low-cost potentials better. These potentials help limit production price increases and maintain the purchasing power of households, which produces a negligible increase of Q_c even up to a 10% cut in emissions. For the tightest targets, the more optimistic results of IMACLIM-S are intriguing, as they apparently contradict its MAC becoming more pessimistic than CES Kvar's beyond a 45% target.

This seeming contradiction can be understood by considering the limit behavior of IMACLIM-S and CES Kvar under ALTER calibration (Fig. 10). The key driver of macroeconomic costs is ultimately, under a full employment hypothesis, the labor intensity of output. Under the envelope approach, the marginal rate of substitution between labor and energy dramatically increases between a 45% and a 55% emissions cut, but the average labor intensity still benefits from the lower costs of the below 45% abatements. Beyond 55% this benefit is exhausted and IMACLIM-S produces higher cost assessments than CES Kvar. At a 58% target, all the ALTER technical asymptotes are saturated and it is impossible to abate more through higher carbon taxes; these have only a nominal impact (scalar multiplication of the price vector) without consequences for the demand and supply levels. The only way of further decreasing emissions is to abandon the full employment assumption and cut back economic activity, thereby reducing them in a linear proportion. Under a CES specification, the average labor intensity grows more slowly and triggers lower real GDP losses. The constant factor substitutability allows carbon emissions to continue decreasing through additional increases in labor intensity—or decreases in labor productivity. Under full employment of a constant labor endowment, this progressively drives real GDP to 0, but more slowly than with the envelope.

5. CONCLUSION

The numerical experiments conducted in this paper argue in favor of revisiting the 'Elephant and Rabbit stew' metaphor. We demonstrate that the an-

Figure 12. Limit Behavior of IMACLIM-S and CES Kvar under ALTER Calibration



swer to Hogan and Manne's 'taste-of-the-stew' question is conditional upon (*i*) the information conveyed by BU analysis of the energy sector, and (*ii*) as they had duly remarked, the magnitude of the departure from reference scenarios required by the policy objectives explored.

A TD framework combining behavioral functions with constant elasticities of substitution and exogenous technical change will satisfactorily approximate any BU analysis not revealing large convexities or singularities in the energy supply and demand—the bias introduced will be negligible for low to moderate departures from the baseline scenarios, and remain tolerable for larger ones. But the same TD framework based on constant elasticities and exogenous technical change will introduce a significant bias in cost assessment, at both ends of the range of policy objectives explored, when calibrated on a BU analysis revealing large flexibilities for low policy targets and saturation effects for higher ones.

That the non-energy supply and demand functions prevailing at some static horizon should evolve along with the energy sector is fully demonstrated by analyzing energy-economy interactions in case of asymptotes to the adaptation potentials. The potentially large substitution possibilities prevailing in a no-policy economy progressively vanish when approaching absolute asymptotes, ultimately consistent with Leontief functions only.

Developing hybridizing methodologies that admit non constant macroeconomic supply and demand functions is all the more important as the analysis goes beyond the aggregate description of the non-energy economy retained in this paper. If indeed saturation effects occur on a single coefficient of a more disaggregated input-output matrix (such as transportation requirements, see e.g. Crassous et al., 2006), this coefficient will operate as a multiplier of policy costs even though, in the reference scenario, the corresponding value share is small.

We do not pretend that the methodology developed in this paper is the only possible one. At the very least it should probably be adapted to fit the specifics of each existing model. Still, we venture to say that its fundamental principles as laid down in section 1 should be respected.

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