Autonomous Energy Efficiency Increases and the MAC curve in Long-Term Energy-Economy Scenarios

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Abstract

Increases in autonomous energy efficiency (AEEI) are the usual means to calibrate energy-economy models to exogenous time paths of energy intensity. This makes it necessary to introduce a compensatory amount of capital to stabilise output prices. The modeller is left with several options where to place this additional capital input in the production function and how to choose the relevant elasticities of substitution. In this paper, several such options are presented, and their consequences for the marginal abatement cost (MAC) curve are esplored. By an appropriate choice of the model setup, it is easily possible to generate either a steeper or flatter MAC curve. As a cautious approach to empirical modelling, a setup that leaves the shape of the MAC unchanged compared to the case of no AEEI is suggested.

Keywords: autonomous energy efficiency increase, marginal abatement cost, rebound effect, computable general equilibrium, climate policy modelling

JEL Code: D58, F18, Q48, Q54

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Non-technical summary

Increases in autonomous energy efficiency (AEEI) are the usual means to calibrate energy-economy models to exogenous time paths of energy intensity. This makes it necessary to introduce a compensatory amount of capital to stabilise output prices. The modeller is left with several options where to place this additional capital input in the production function and how to choose the relevant elasticities of substitution.

In this paper we present three such options: (1) placing the additional capital as a perfect complement at the highest nest of the production tree, (2) adjusting the amount of "normal" capital use in the value-added nest of the production function, (3) introducing "energy-use capital" at the lowest nest (energy inputs) of the production function. We explore the consequences of these calibration alternatives for the marginal abatement cost (MAC) curve. We find that (1) there is a general tendency of AEEI in all possible forms to shift the MAC curve upwards. (2) Introducing "energy-use capital" at the lowest nest (energy inputs) of the production function generates a "dilution effect" for the policy measures that increase the price of the energy carriers, and a substitution effect between energy and energy-use capital. For high values of the elasticity of substitution between the energy carrier and energy-use capital the second effect can dominate, so that the MAC curve flattens as a result of AEEI.

We conclude that as long as no empirical foundation for shifts in the MAC curve through AEEI is available, we should aspire at an approach that is as "neutral" as possible and avoids any systematic, but arbitrary, bias. We view our calibration variant that leaves the shape of the MAC (roughly) stable.(with an intermediate value of the elasticity of substitution) as the most promising candidate for such a "cautious" approach to AEEI modelling. However, a better empirical foundation of the calibration is highly desirable. The options of simulating the relation of AEEI and the MAC in bottom-up energy-system models must therefore be explored.

1 Introduction

In long-term energy-economy studies it is common practice to calibrate a computable general equilibrium (CGE) model to exogenous time paths of GDP and energy use growth rates. This calibration procedure is important, because the shape of this reference (or "business as usual", BAU) scenario can bear heavily on the simulation outcomes. As a typical application, consider the case that we want to assess the economic cost of a country's or region's commitment to a greenhouse gas emission ceiling ("Kyoto" type policy). Such ceilings are usually formulated as a percentage of the emissions at a historical point in time (1990 in the case of the Kyoto protocol). However, the economic tightness of the ceiling is not determined by this backward-looking comparison, but by the difference between the target and the counterfactual emissions in the case of no ceiling (i.e. the BAU). One and the same emission reduction (as a percentage change with respect to the past) can be a tight restriction for a country that would have a high growth rate of emissions otherwise, while it is less severe for a country with a low BAU growth rate. Differences in the countries' BAU emission growth rates are in turn determined by their respective growth in GDP, energy intensity (energy use per unit of GDP) and emission intensity of energy use (through the switch between different energy carriers). These data are usually taken from long-term projections of GDP and energy use (e.g. WEC/IIASA (1998) scenarios). The usual CGE calibration procedure is then to use a static benchmark year dataset (for most international CGE models this is the GTAP database: Dimaranan and McDougall, 2006) to keep its structure constant over time with two exceptions: (1) autonomous factor productivity increases to accommodate the GDP growth and (2) autonomous energy efficiency increases (AEEI) to account for the changes in energy intensity and the structure of energy use. In this paper we are concerned with the consequences of the latter.

The basic idea of AEEI – as with all autonomous efficiency changes in economic models – is that one unit of physical input translates into potentially more than one economically "efficient unit" of input as a consequence of technological progress. The paradigm in the case of energy efficiency is the use of more efficient power generators that transform a given amount of the energy carrier into more units of usable energy as before. More efficient use of energy (e.g. space heating with better insulation or light generation using LEDs instead of conventional light bulbs) can be conceptualised along these lines. However, it should be kept in mind that it is a rather heroic assumption that *all* projected changes in energy efficiency are due to such AEEI.

If AEEI is our choice for calibrating the model to exogenous changes in energy intensity, we face follow-up questions. First, introducing AEEI in the model alone does not guarantee that the use of the respective energy carrier will actually fall. On the one hand, energy demand (in physical units) for a *given* amount of energy use (in efficient units) decreases, which works in the desired direction. On the other hand, increased energy efficiency leads to lower energy prices per efficient unit, and this in turn will drive up demand (the so-called "rebound effect"). The net effect is not clear in advance, and there are constellations where calibration to given exogenous changes of energy use becomes difficult or even impossible. Therefore AEEI is usually complemented by an compensating increase in other inputs to production, so that the output prices are stabilised and the rebound effect is dampened. Our examples of real-world efficiency increases (more efficient engines, better insulation) suggest that we should think of these compensatory inputs as additional capital inputs (better and more expensive energy-use capital).

The second consecutive question to be answered is where to place the compensatory capital input in the production function. In this paper, I review three options and explore their consequences for the overall behaviour of the calibrated model. These options are: (1) placing the additional capital as a perfect complement at the highest nest of the production tree, (2) adjusting the amount of "normal" capital use in the value-added nest of the production function, (3) introducing "energy-use capital" at the lowest nest (energy inputs) of the production function.

These options are compared with respect to the marginal abatement cost (MAC) curves they produce. A fully specified static CGE model (without any AEEI) produces in most cases a nicely shaped, convex MAC curve. The question that we try to answer is: How does the steepness of this curve change if we introduce AEEI (in the three different ways listed above)? The consequence of the shape of the MAC curves for different kinds of policy relevant analyses is straightforward. If we find that the introduction of AEEI flattens the MAC curves, this will introduce a tendency to postpone abatement activities into the future, because abatement becomes cheaper in the course of time. If, to the contrary, AEEI makes the MAC curves steeper, this will create a tendency for early action. In optimal timing studies like Böhringer, Löschel and Rutherford (2006), this should immediately translate into a shift of the optimal emission profile in either direction.

Comparative runs with the model WorldScan, in which we implemented all three variants of introducing compensatory capital, produced the following results: (1) In general, there seems to be a strong tendency of “energy-use capital” to produce a steeper MAC curve. Examples for this can be found in all three variants of the AEEI calibration. (2) With energy-use capital at the lowest nest of the production tree, this tendency can be counteracted by a high elasticity of substitution between energy and energy-use capital. In this case flatter MAC curves than without AEEI are possible.

The following sections present the individual steps to these results. Section 2 introduce the different options of modelling AEEI in more detail. Section 3 traces out the consequences for the resulting MAC curves. Conclusions are drawn in Section 4. An Appendix provides additional information about the AEEI calibration procedure in the different model variants.

2 Modelling energy efficiency in a CGE framework

The basic idea of an autonomous energy efficiency increase (AEEI) can be implemented in a CGE framework with a single productivity parameter. This parameter, $\gamma > 1$, transforms one physical unit of the energy carrier into γ efficient units. At the same time it determines the relation between the price of a physical and an efficient unit. The input decisions of the firms are governed by the accounting in efficient units and prices, energy use and emission accounting is in terms of physical units.

As mentioned in the introduction, there is both a plausibility reasoning and a practical necessity for not remaining with this most basic approach. The practical necessity results from the rebound effect. While reducing the demand in physical units *per efficient unit*, AEEI lead also to a price drop for efficient units and hence to an increase in demand (see Brännlund et al., 2007, for an example of an empirical approach to this phenomenon). It depends on the parameters in the model (ease of substitution between energy carriers, between energy and other production inputs, and elasticity of demand) whether a higher energy efficiency will actually increase or decrease the demand for an energy carrier (in physical units). We cannot rule out that the demand curve (as a function of energy efficiency) is flat or even non-monotonous, so that the calibration of the model to exogenous levels of demand for energy carriers become a difficult or unsolvable task. Therefore AEEI is usually combined with an compensating increase in capital inputs, so that the output prices are stabilised and the rebound effect is dampened. This fuel-use capital is also an outcome of plausibility reasoning, because efficiency increases should not be considered as a free lunch. The examples of real-world efficiency increases (more efficient engines, better insulation) that come to our mind obviously are costly, and these costs must be implemented in the model.

This produces follow-up problems to be solved? How to determine amount of additional capital? And where to place this capital in the production structure? The amount of additional capital can in principle be determined through empirical engineering studies (see, e.g., CRA (1997) for the case of fuel efficiency of passenger cars). However, by their nature, these studies are specific to particular uses, and it is difficult to aggregate them to the level of sectoral production functions as they are found in CGE models. Therefore the necessary amount of energy-use capital is usually determined by some ad-hoc rule. The ad-hoc rule implemented in WorldScan (Lejour et al., 2006) says that the amount of energy-use capital must keep the sectoral output price fixed at the benchmark input prices. This implicitly assumes a straight isocost curve between energy and energy-use capital, where all combinations produce the same profit level. In the benchmark situation, no energy-saving capital goods are available or they are too expensive (as they cannot be observed, this question cannot be answered). With AEEI they become available, and their cost is implicitly determined by the requirement that the output price remains constant at benchmark prices.

The second follow-up question is where to place the compensatory capital input in the production function. To get an overview of the options, recall the typical sectoral production function in a CGE model. Figure 1 shows the case of WorldScan

(Lejour et al., 2006). As in virtually all applied general equilibrium models, sectoral production is represented by a nested constant-elasticity-of-substitution (CES) function. In the context of energy modelling, we are particularly interested in the lower levels of the production nesting. The energy nest (lower right-hand part of Figure 1) is first decomposed into electricity and non-electricity, non-electricity comprises coal and non-coal as subnests, and non-coal is finally disaggregated into oil, gas, renewables and biomass.

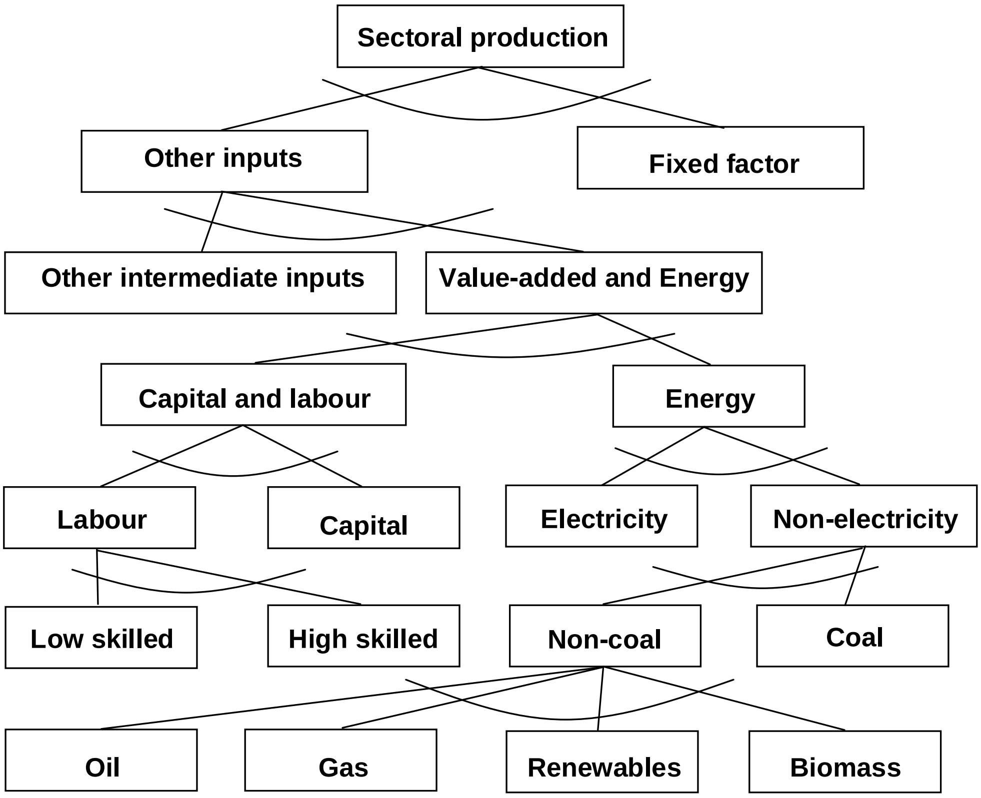

Figure 1: Production nesting in WorldScan

The introduction of the AEEI parameter γ for the fossil fuels coal, oil and gas in such a nested CES structure is straightforward. For the placement of the compensatory capital, we consider three options:

1. Placing the additional capital as a perfect complement at the highest nest of the production tree.

2. Adjusting the amount of "normal" capital use in the value-added nest of the production function.
3. Introducing "energy-use capital" at the lowest nest (energy inputs) of the production function.

The first approach is mostly driven by the desire to keep the model simple and basically accepts our ignorance about the actual details of efficiency-augmenting capital use. It consists of introducing the additional capital as a perfect complement at the highest nest of the production tree (see Figure 2). An example is the model PACE (reference?).

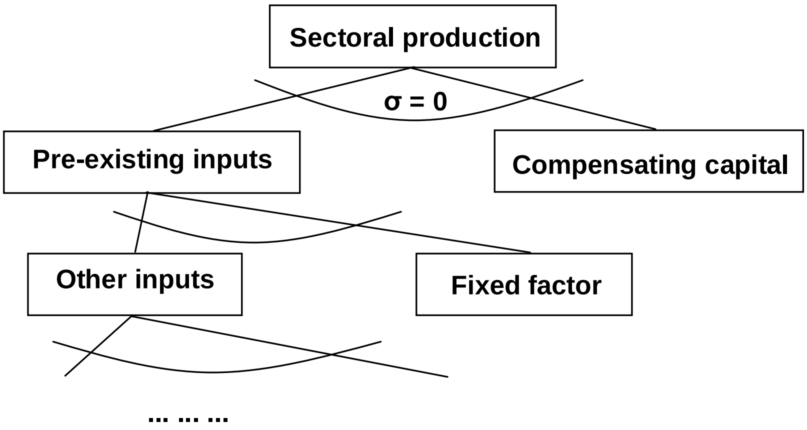

Figure 2: Calibration approach (1)

The second approach is similar to the first in that it introduces energy-use capital at a single place in the production nesting, this time by adjusting the autonomous efficiency of capital use. In the standard case of an AEEI for the fossil fuels that accounts for decreasing energy intensity of production, this would amount to a decrease in the efficiency of capital use, reflecting the additional capital for more efficient energy use equipment. This calibration procedure is driven by the desire to keep the production structure as similar to the situation before the adjustment as possible. Particularly, capital remains a homogeneous input, contrasted to calibration (1), where it enters the production structure at two different places.

Calibration procedures (1) and (2), while addressing the core difficulty of the rebound effect, produce two follow-up problems. First, the rebound effect is only eliminated at the level of the sectoral output. This is actually the most visible and most discussed form of the rebound effect. (Take as an example the increase in demand for transport services as a reaction to means of transportation that use less fuel.) But it is not the only one. There are also rebound effects within the production function, to the extent that other inputs are substituted by energy, whose cost has been decreased to the extent of the efficiency increase. Such within-production rebound effects are clearly the more pronounced the higher the elasticity of substitution between different inputs.

A second follow-up problem results if we try to calibrate the model to the development of not only one but several energy inputs simultaneously. Any AEE change has not only consequences for the energy carrier for which it has changed itself, but also for the other carriers. Depending on whether they are substitutes or complements, a lower price for one carrier (produced through an AEEI) will lead to lower (higher) demand for the other carriers. This can lead into problems, which can most easily be understood with the extreme case of perfect complements in mind. In this extreme case, an AEEI for one energy carrier leads to a totally parallel movement of the demand of all carriers. If the exogenous baseline prescribes different intensity growth for different carriers, this cannot be accommodated in the model at all.

In applied models, the situation is of course not that severe. Energy carriers are never modelled as perfect complements. But in any case we face a dilemma. If the elasticity of substitution between energy carriers is low, we get problems with the independent calibration of the individual carriers. If it is high, then the model produces a high within-production-function rebound effect. In practical applications, either of the problems can easily occur at least for a subset of sectors and/or regions.

These practical problems with calibration are the reason that we propose third calibration method, which is now implemented in WorldScan. We introduce "energy-use capital" at the lowest nest (energy inputs) of the production function, separately for each energy carrier (see Figure 3). Against the background of the discussion above, this has mainly three advantages:

- It is relatively close to our intuitive understanding of "higher energy efficiency through better technology". Fuel-use technology is carrier-specific, and it inter-

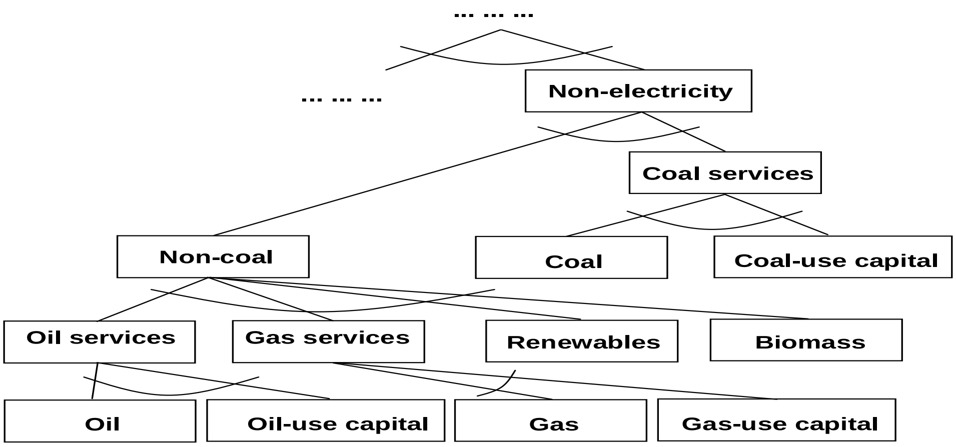

Figure 3: Calibration approach (3)

acts directly with the respective energy input, rather than somehow modifying the general capital stock in production.

- It blocks within-production-function rebound effects through stabilising the price of an effective energy unit ("energy service" in Figure 3) at the lowest level possible. Energy efficiency increases for one carrier do not lead to large substitution effects away from other carriers, because the relative prices of energy services from different sources do not change as much as they would if compensating capital is introduced at a higher level of the production function.
- It leaves us with additional parameters for fine-tuning, namely the elasticity of substitution between the energy-carriers and the corresponding energy-use capital. As the calibration will turn out to affect the steepness of the MAC curve, we need such parameters for correction. (At the same time free parameters are a curse as long as we lack the empirical data to determine their value. Later we will assume that the elasticity of substitution is the same for all fossil fuels and in all regions, thus reducing the degrees of freedom to one.)

In the next section, we explore the consequences of the different calibration methods for the marginal abatement cost curve.

3 Energy efficiency and the MAC curve

The precise definition of a marginal abatement cost (MAC) curve is not uniform in the economic literature. In the context of CGE models, MAC curves can best be thought of as inverted curves of emission certificate prices: Which level of the certificate price would be necessary to drive emissions in the economy down to the desired level? A fully specified static CGE model (without any AEEI) usually produces a nicely shaped, convex MAC curve. The question that we try to answer is "How does the shape of this curve change if we introduce AEEI in the different ways listed in Section 2). The consequence of the shape of the MAC curves for different kinds of policy relevant analyses is straightforward. If we find that the introduction of AEEI flattens the MAC curves, this will introduce a tendency to postpone abatement activities into the future, because abatement becomes cheaper to the extent that energy efficiency rises. If, to the contrary, AEEI makes the MAC curves steeper, this will establish a tendency for earlier abatement activities. In optimal timing studies like Böhringer, Löschel and Rutherford (2006), this should directly translate into a shift of the optimal emission profile.

To get a clear picture of the interaction of AEEI calibration and the MAC curves, we perform some stylised simulations with the model WorldScan. We simulate general equilibrium MAC curves by imposing emission targets that steadily increase in strictness, until we arrive at 50% of the initial emission level. More specifically, we impose a worldwide emission target and assume a globally efficient permit trading system (or, equivalently, a worldwide uniform emission tax). "General equilibrium" MAC curves means that we capture all economic costs of the abatement of emissions, not only the direct costs of the more efficient technologies. (As a considerable part of the emission reduction is by inducing a reduction in energy demand, accounting for only the direct costs would be misleading.) The lowest curve in Figure 4 shows the MAC curve in the case of no energy efficiency increase. It takes the conventional convex form, which reflects declining ease of substitution if we depart from the initial equilibrium. Observe that the model only accounts for substitution possibilities

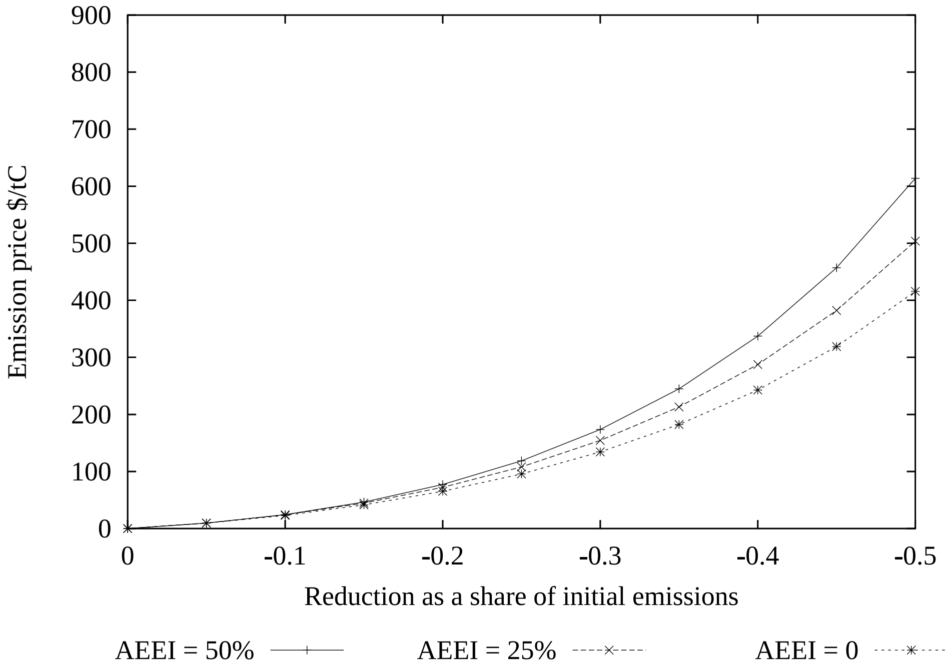

Figure 4: MAC curves with calibration (1)

within the existing production technology. Backstop technologies are not considered, so that the MAC curve proceeds into regions where alternative technologies (most notably carbon capture and sequestration) become economically viable. We remain with this simplified picture to focus on the question of interest.

The two other curves in Figure 4 (labelled "AEEI = 50%" and "AEEI = 25%") show the effect of an increase in energy efficiency on the MAC curve with calibration procedure (1), i.e. the introduction of compensating capital as a perfect complement at the highest level of the production function. We imposed an autonomous reduction of energy use of 25 and 50 percent, respectively. (To avoid the picture to be blurred by composition effects, the efficiency increase is assumed homogeneous across all fossil fuels.) After this initial adjustment, we assess again the consequences of emission reductions of up to 50 percent through a carbon permit policy. It can clearly be seen that starting from a higher level of efficiency shifts the MAC curve upwards. With the energy efficiency doubled at the initial point ("AEEI = 50%") the MAC at any given point of relative reduction also almost duple. Observe that in Figure 4, we compare relative emission reductions. Of course, the same relative reduction from a different starting level means a different absolute reduction. As benchmark emissions in case "AEEI = 50%" are only 50 percent of the case "AEEI = 0%", absolute reductions at the right-hand edge of the figure are also only 50 percent. If we would scale the figure so that absolute emission reductions are compared, the difference between the curves would be even more pronounced. The curve "AEEI = 50%" would then end with its value of about 600$ at -0.25. However, emission reductions as a percentage of initial emissions seem to be a reasonable standard of comparison. If we assumed that energy efficiency increases without any compensating capital input, and that the elasticity of energy demand is one, so that the reduction of the effective price to one half leads to a doubling of the energy demand, we would end up with not much more than a re-scaling of energy units. (Of course, there would be general equilibrium feedback effects that disturb the exact equivalence.) In this case, we would expect the MAC curve, expressed in relative reduction terms, to remain (almost) unchanged.

Figure 5 is the analogue to Figure 4 for the second calibration method (decreasing capital efficiency to compensate for higher AEE). Both figures show the same qualitative traits, and they are also quantitatively very similar. In fact, the MAC curves for higher energy efficiency are somewhat lower in case (2).

In the case of the third calibration procedure (introduce compensatory capital input at the lowest nest of the energy input structure), we are left with an additional degree of freedom, because we can choose between different values of the elasticity of substitution between the fossil fuels. (Strictly speaking, there are even as many degrees of freedom as there are fossil fuel carriers, because, in principle, we can choose each of the elasticities independently. However, in the present analysis we remain with a uniform elasticity of substitution.)

Figure 6 shows the case of an elasticity of substitution of zero, i.e. fossil fuels and capital (fuel-using equipment) are perfect complements. As expected with the similar setup to calibration (1), the results are again qualitatively the same. Now the MAC curves for the cases of an efficiency-driven reduction of energy use by 25 and 50 percent are even higher than with calibrations (1) and (2).

Figure 7 shows a polar case of a high elasticity of substitution between fossil fuels and fuel-use capital: 0.9. Now the order of the curves is reversed: The MAC are lower with higher levels of energy efficiency.

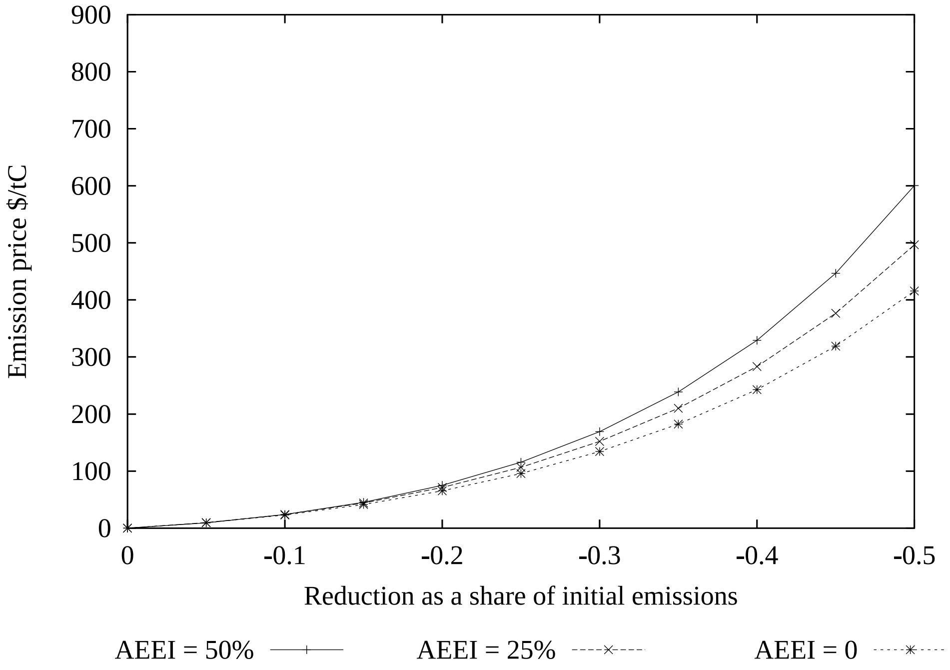

Figure 5: MAC curves with calibration (2)

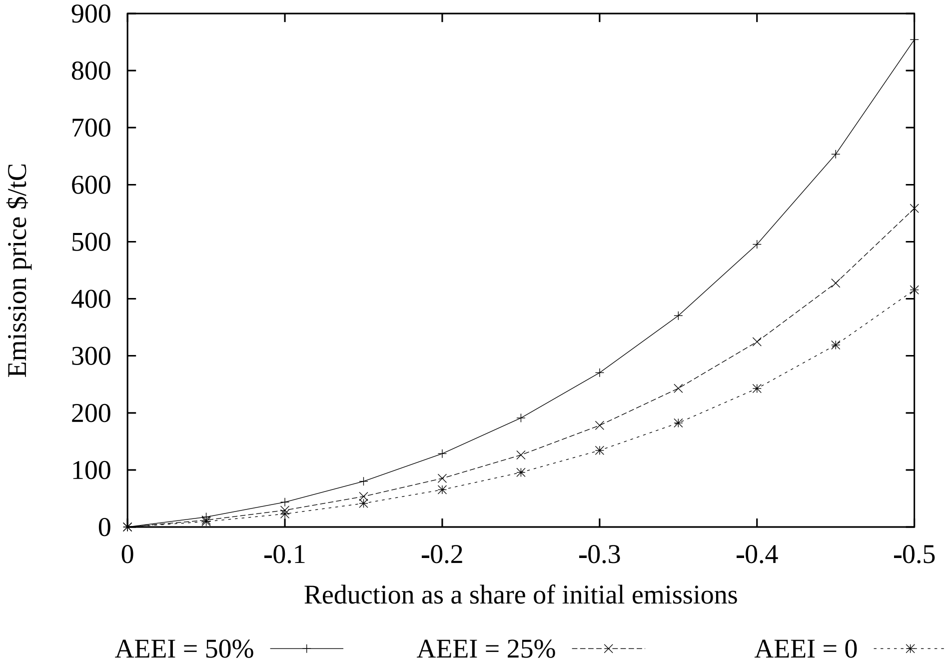

Figure 6: MAC with calibration (3), elasticity of substitution: 0.0

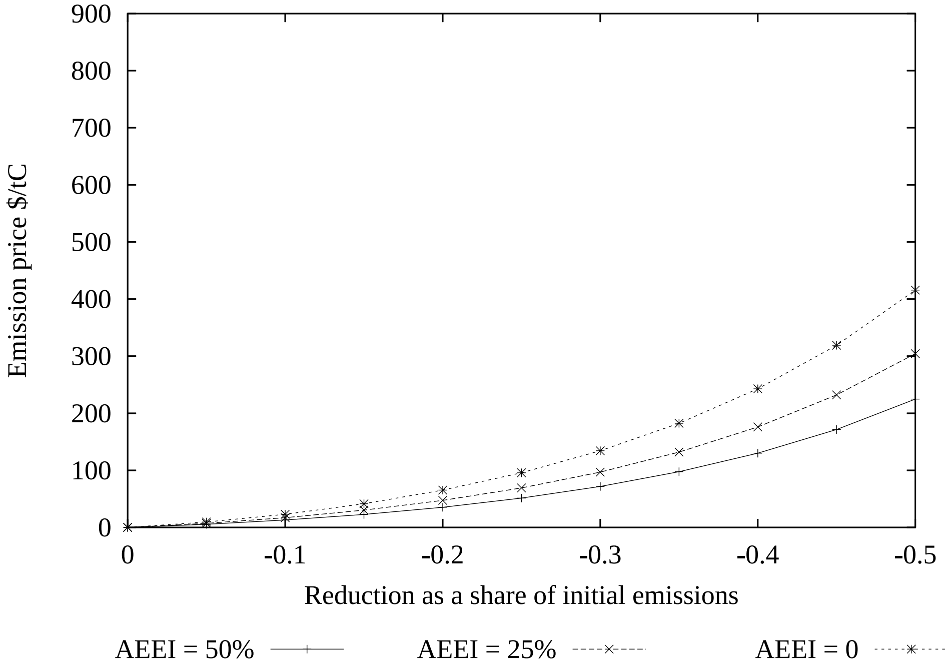

Figure 7: MAC curve with calibration (3), elasticity of substitution: 0.9

Given the polar cases of Figures 6 and 7, we can expect that there is a intermediate case of the elasticity of substitution which leaves the MAC curves (almost) constant. Figure 8 shows the case of an elasticity of substitution of 0.5, which is very close to this critical value.

The differences between Figures 6, 7 and 8 can be straightforwardly traced back to two countervailing effects. The first effect is the composite price effect. With an AEE parameter exceeding one, the price of an efficient unit of energy is composed of the fuel component and the complementary capital component. The higher the energy efficiency, the higher the share of capital in this composite price. This means that a given increase in the price of the energy carrier itself (through a emission tax or permit price) translates into a lower increase of the composite price and therefore into a lower substitution effect. Turned around: The tax must be higher in order to affect a reduction in energy use of a given size. This effect is the only one present in the variant with at elasticity of substitution of zero (Figure 6) and causes the MAC curves to be steeper, the higher the energy efficiency.

By introducing substitutability between the energy carrier and capital (which

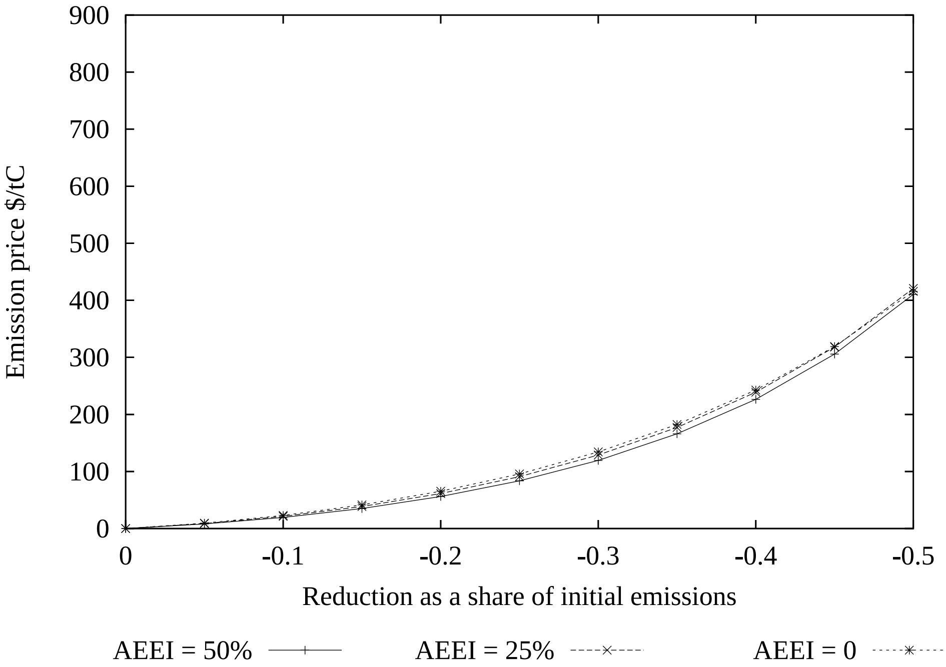

Figure 8: MAC with calibration (3), elasticity of substitution: 0.5

means further energy efficiency increases that are induced by the simulated energy policy), we create an opposite effect. The higher this substitutability, the easier it is to switch from energy to capital use, and consequently the MAC curve flattens. This occurs when we move from Figure 6 to 8 and 7. At intermediate values of the elasticity of substitution, the two effects approximately balance and we end up with an almost unchanging MAC curve (Figure 8).

The following observations still need a more careful analysis:

- What is the driving force of the increase in the MAC with calibrations (1) and (2)? A decomposition in substitution effects (between energy carriers) and demand effects could be revealing here.
- Why are the results of (1) and (2) so similar? Given that the substitutability between energy and existing capital is higher than with the perfect complementary capital at the highest nest of the production function, one might have expected that MAC curves are considerably flatter under calibration (2) than under (1).

4 Conclusions

We presented three options of modelling autonomous energy efficiency increases (AEEI) in general equilibrium models for the analysis of long-term energy-economy scenarios: (1) Placing the additional capital as a perfect complement at the highest nest of the production tree, (2) adjusting the amount of "normal" capital use in the value-added nest of the production function, (3) Introducing "energy-use capital" at the lowest nest (energy inputs) of the production function. These options can be used to calibrate the CGE model at hand to a given long-term business-as-usual path of energy use by carrier.

Compared to the first two calibration methods, the third one is characterised by the following advantages:

- It is relatively close to our intuitive understanding of "higher energy efficiency through better technology". Fuel-use technology is carrier-specific, and it interacts directly with the respective energy input.
- It blocks within-production-function rebound effects through stabilising the price of an effective energy unit at the lowest level possible. Energy efficiency increases for one carrier do not lead to large substitution effects away from other carriers, because the relative prices of energy services from different sources do not change as much as they would if compensating capital is introduced at a higher level of the production function.
- It leaves us with additional parameters for fine-tuning, namely the elasticity of substitution between the energy-carriers and the corresponding energy-use capital. As the calibration will turn out to affect the steepness of the MAC curve, we need such parameters for correction.

Comparative runs with the model WorldScan, where we implemented all three calibration procedures, produced the following results:

- There is a general tendency of AEEI in all possible forms to shift the MAC curve upwards. This is the dominant effect in calibration methods (1) and

(2). With method (3), this effect dominates for low levels of the elasticity of substitution between the fuel carrier and fuel-use capital.

- Introducing "energy-use capital" at the lowest nest (energy inputs) of the production function (calibration method (3)) generates a "dilution effect" for the policy measures that increase the price of the energy carriers. The cost of efficient energy use is now a composite of the price of the energy carrier and capital. A price of emission permits affects energy demand the less, the higher the share of capital in the user cost of energy (and thus the higher the energy efficiency).
- To this adds a substitution effect between energy and energy-use capital. This effect is the larger the higher the value of the elasticity of substitution between the energy carrier and energy-use capital.
- For high values of the elasticity of substitution between the energy carrier and energy-use capital the second effect can dominate, so that the MAC curve flattens as a result of AEEI.

Given the importance of the MAC curves for policy assessment and our empirical ignorance about the actual interaction of energy efficiency and abatement costs, this must be regarded as an issue to be handled with great care in policy oriented studies. We argue for the following guideline:

- As long as no empirical foundation for shifts in the MAC curve through AEEI is available, we should aspire at an approach that is as "neutral" as possible and avoids any systematic, but arbitrary, bias. We view our calibration variant that leaves the shape of the MAC (roughly) stable.(with an intermediate value of the elasticity of substitution) as the most promising candidate for such a "cautious" approach to AEEI modelling.
- A better empirical foundation of the calibration is highly desirable. The options of simulating the relation of AEEI and the MAC in bottom-up energy-system models must therefore be explored.

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A Appendix

A.1 Issues in the calibration of the AEEI parameters

In this appendix I further explore the problems that can occur with the different versions of AEEI calibration. We start with the simplest form of an adjustment, the introduction of an efficiency parameter for energy without any compensation. Figure 9 shows the effect of a uniform increase in the energy efficiency in all regions and for all carriers.

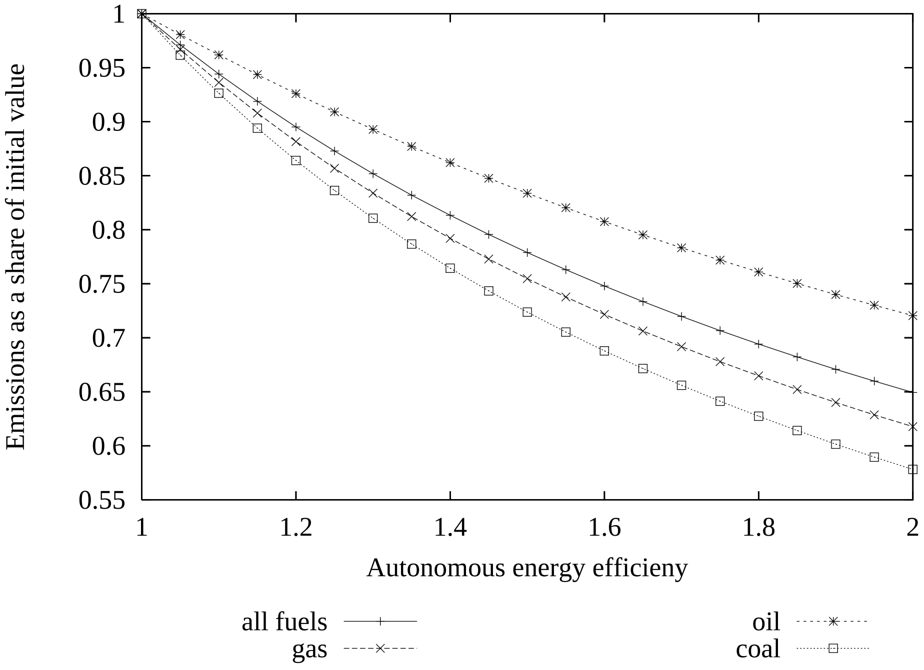

Figure 9: Effects of a uniform, uncompensated AEEI

Figure 9 shows that in the aggregate, the effects are smooth and well-behaved. Uncompensated AEEI leads, just as one would naively expect, to lower levels of energy use. There is a certain rebound effect; without any rebound, we would arrive at a level of 0.5 at the right hand side of Figure 9. However, this effect is moderate on average, ranging from less than 20% for coal to about 50% for oil. All in all, Figure 9 does not give strong support for the necessity of a compensating increase of capital use.

Table 1 decomposes the effect of a uniform AEEI by region. We can see that most of the regions are quite close together. Energy use reductions with an energy efficiency of twice its initial value are between 0.49 and 0.67 for coal (this means that there is even a slightly negative rebound effect in two regions), 0.69 and 0.81 for oil, and 0.56 and 0.71 for gas. The only country that totally disturbs this picture are the Netherlands. Here the energy use is not only significantly higher than in all other regions, the rebound effect is even far beyond 100 per cent, so that we end up with an increase in energy use instead of a reduction. Obviously, there is a special problem with the data of the Netherlands. We will further explore this and also try a model version where NLD is lumped together with some other region.

Table 1: Effects of a uniform AEEI by region and carrier

Region	coal	oil	gas	Region	coal	oil	gas
DEU	0.60	0.79	0.64	FSU	0.64	0.80	0.70
FRA	0.49	0.77	0.68	TUR	0.67	0.81	0.68
GBR	0.58	0.76	0.59	USA	0.60	0.70	0.60
NLD	1.15	2.23	1.15	AUS	0.62	0.74	0.59
ITA	0.53	0.73	0.62	BRA	0.49	0.73	0.62
ESP	0.59	0.77	0.71	LAT	0.59	0.69	0.56
EUO	0.57	0.76	0.63	MNA	0.65	0.75	0.63
EUN	0.59	0.74	0.63	CHI	0.59	0.71	0.71
REU	0.60	0.71	0.58	IND	0.64	0.72	0.62
CAN	0.60	0.74	0.64	AAR	0.60	0.74	0.59
ROE	0.52	0.71	0.63				

Figure 9 is certainly too optimistic as to the extend the rebound effect, because we assumed a simultaneous increase in the energy efficiency of all fossil fuels. Any within-production rebound effect among the fossil fuels remains thus out of the picture. Figure 9 will therefore be complemented by the case where AEEI is introduced for each fuel individually.

A.2 Issues in the comparison of MAC curves

In all figures where we compare MAC curves (starting with Figure 4), we implicitly assumed that the marginal cost for a relative reduction in emissions is a reasonable standard of comparison. This is in line with other papers that touch the issue of MAC comparisons (particularly Baker et al., 2006, p.6), but it is not the only possible approach. Figure 10 shows again the MAC curves from Figure 4, but now scaled in terms of reduction relative to the initial level of emissions.

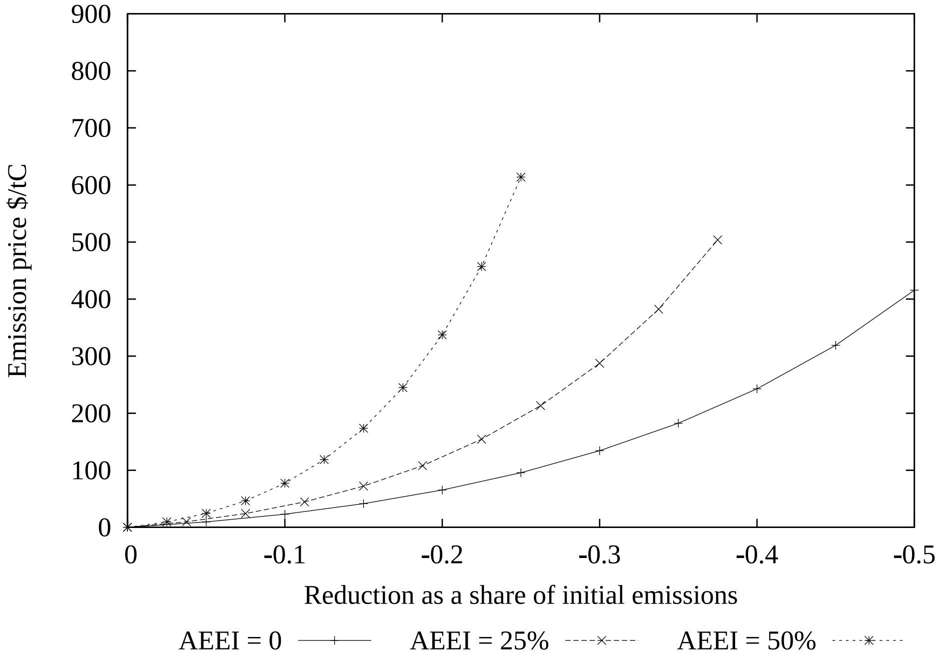

Figure 10: MAC curves: in terms of initial emissions (relative)

In the case of “AEEI = 50%”, we start from a level of 50 per cent of initial emissions. A 10 per cent reduction from that starting point is only 5 per cent of the total initial emissions. If we take this into account, the curves become the steeper the lower the level of initial emissions (and thus the higher the level of AEE). The difference between the curves is then amplified.

In Figure 11, we also visually take into account that we start at different levels of emissions. The curve “AEEI = 50%” therefore does not start at “0” any more, but at “-0.5”, because a 50 per cent reduction has already been achieved through energy efficiency increases. If we compare the slope of, e.g. the “AEEI = 25%” with the slope of “AEEI = 0” *at the same level of absolute emisions* the difference looks less severe than initially. Even more so if we adjust the curves in a way that they start with zero at the same point as the curve we compare it with (“AEEI = 0, adj” and “AEEI = 25%, adj”). This is plausible, because we are interested in

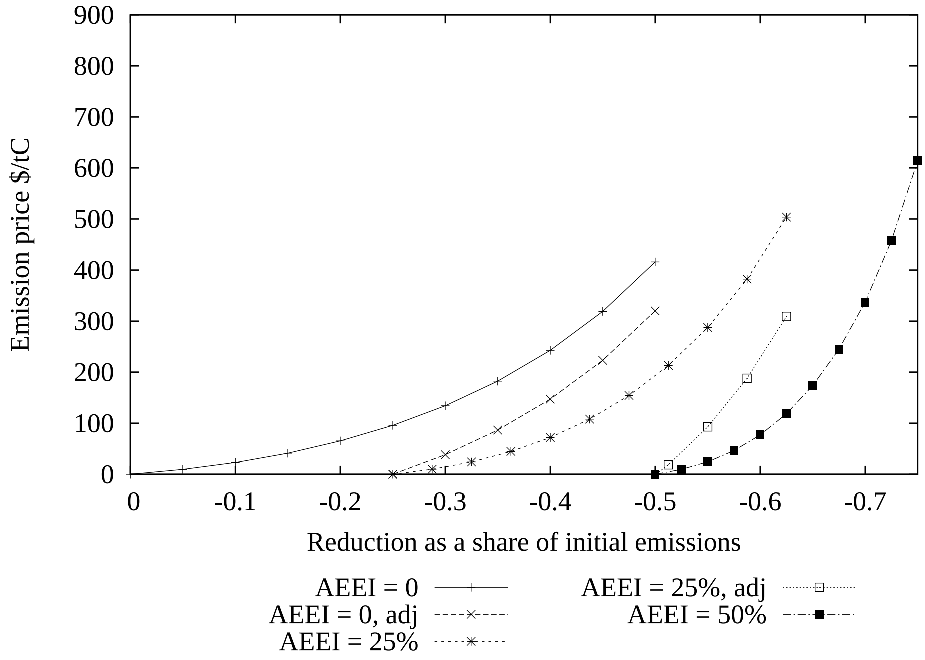

Figure 11: MAC curves: in terms of intitial emissions (relative and absolute)

costs of *additional* reductions. However, it becomes apparent that any MAC curve with a positive AEEI starts with a slope of zero (because no additional abatement is optiomal with no change of incentives), whereas a curve that has been shifted downwards must start with a positive slope.

From these different ways of comparison, none stands out as particularly intuitive or theoretically justified. The standard of comparison can therefore only be determined with a certain degree of arbitraryness.