Costs and potentials of energy savings in European industry – a critical assessment of the concept of conservation supply curves

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Abstract

Conservation supply curves (CSC) were developed to describe and compare the different options for energy conservation in a transparent way. They show the quantity of conserved energy as well as the costs related to specific saving options and thus provide an indication of which options are to be preferred to ensure cost-effectiveness. Furthermore they play a key role in many energy and climate policy models.

The construction of CSC, however, is subject to several methodological issues that have an enormous impact on the slope and position of the final curve. Some of these issues are related to path dependency, the assessment of costs for distinct saving options, the choice of "perspective", the uncertainty related to the estimation of the relevant saving potential or the choice of parameters like energy price forecasts. A critical analysis of these methodological issues and their impact on the final curve is the main goal of this paper. This will be supported by the construction of an exemplary CSC for European industry in order to indicate the quantitative effects involved.

By analysing the influence of these methodological issues on the final CSC, this paper contributes to a better understanding and interpretation of the useful but highly uncertain concept of CSC and aims to enhance the discussion about cost effectiveness in energy conservation, which is the basis for successful policy implementation.

Although the focus of this paper is on (energy) CSC, the very similar marginal greenhouse gas abatement cost curves are also considered as these are based on the same methodological approach and are becoming more widespread in the discussion of the possibilities and costs of climate change mitigation.

Introduction

Since the 1980s, conservation supply curves (CSC) have been widely applied in energy system analysis and modelling as well as for the analysis and visualisation of conservation potentials and costs.

Although initially developed to show the costs and potentials of energy conservation, CSC are increasingly being used in climate policy to visualise distinct options for greenhouse gas abatement and compare their potentials and costs and are a crucial input to climate change abatement models. In this case, the curves are generally called marginal abatement cost curves (MACC), but the underlying methodology is still very much the same, only that cumulated energy savings are replaced by cumulated greenhouse gas (GHG) abatement. The development from CSC to MACC is also associated with an extension of the options shown on the curves. While CSC focus exclusively on energy conservation and thus a reduction of energy demand, MACC have a wider focus and also consider greenhouse gas (GHG) abatement options on the energy supply side and even non-energy related GHG abatement options, for instance in agriculture.

Despite the seeming simplicity and clarity of CSC, the methodology for their construction is not as straightforward as the curves may imply. A number of methodological decisions have to be taken when constructing CSC and most of these have substantial effects on the results. This paper presents the most important methodological issues and estimates their influence on the resulting curve. Awareness of these issues is crucial for both users of CSC so that they can accurately interpret the results and for the designers of CSC. Knowledge of the methodological possibilities is essential to be able to compare independent CSC from different studies.

This paper is structured as follows. First, we show the fields where CSC are applied and then give an introduction to the theoretical concept of CSC. Based on the theoretical background, we construct a CSC for European industry, which is used to support the following discussion of methodological issues by providing estimations of the quantitative impacts on the final curve. At the centre of the paper lies the discussion of the methodological issues and shortcomings related to the construction of CSC. Finally we summarize all the discussed effects in a concluding table.

THE APPLICATION OF CONSERVATION SUPPLY CURVES AND MARGINAL ABATEMENT COST CURVES

Three important applications of CSC are briefly presented in this chapter. The first is in energy analysis related to energy efficiency, the second in energy modelling and the third is the use of MACC in global climate negotiations.

The application of CSC in energy analysis dates back to Meier et al. (Meier 1982; Meier 1983), who analysed energy saving potentials in California's residential sector. Since then, CSC have been widely used in energy analysis as a way of comparing the different options for energy conservation in terms of both the achievable saving potential and the related costs. They make it possible to instantly identify those conservation options with the lowest costs and the highest saving potentials.

CSC are used in most energy system models that forecast energy demand (Niklasson 1995; Worrell et al. 2004). The curves determine the cost-effectiveness of investment in energy conservation and thus, in models that base investment decisions on the cost-effectiveness criterion, the future energy demand.

MACC are playing an increasingly important role in climate negotiations. This is reflected by the frequency with which global MACC created by the McKinsey group for Vattenfall are cited and used in presentations at the meetings of the UNFCCC, for instance in the discussion of the technical framework (e.g. Bazilian et al. 2009) or of burden sharing among Annex-I countries (e.g. den Elzen et al. 2008). MACC play different roles, the most important of which are probably the three described below.

The first is as a means to split the burden of reducing emissions among developed (Annex I) countries (burden sharing). In this sense, the MACC is one of many variables. It is a way of integrating the emission reduction potential available in specific countries into the negotiations. One argument could be that each country should bear the same financial burden. Following this argument, countries with higher abatement cost, such as Japan (compare Klepper, Peterson 2006), would have to do less. This concept was in fact suggested by Japan in a workshop of the Ad Hoc Working Group (AWG) of the Kyoto protocol at COP 13 in Poznan (Moriya 2009).

A second way MACC can be used is as a tool to evaluate the various existing burden sharing approaches. Den Elzen et al. (2008) evaluated two allocation schemes (the Multi Stage Approach and the Contraction and Convergence approach) using MACC. They found that the allocation scheme did not strongly influence the induced costs, but rather that baseline assumptions and the assumed stabilization level play a more important role.

A third role of MACC is to compare the implications of different stabilization pathways. Den Elzen et al. (2009) found, for instance, that emission reduction costs can be reduced by choosing a peaking profile pathway over a stabilization pathway. With a peaking profile pathway, CO_2 concentration is further reduced after stabilization is reached. They argue that cost reductions of up to 40% can be achieved when trying to reach a certain temperature threshold with the same likelihood as the stabilization profile. The reason is that the additional mitigation efforts needed for the peaking profiles take place at a later point in time and will be cheaper.

As the Stern Review (Stern et al. 2009) demonstrated, any evaluation of how much global warming mitigation is going to cost will always be a crucial part of international negotiations and MACC will always have an important role to play in better understanding the issues involved.

The concept of conservation supply curves

CSC are usually constructed based on the assessment of individual conservation options, such as the introduction of high-efficiency electric motors. For each of the considered options, the conservation potential and the related specific costs are assessed and the options are ranked according to their costs (see Figure 1). The individual options are plotted on the graph in a least-cost order from left to right. As a result, the curve is shaped like a ladder, where each step represents one conservation option. Typically the least-cost conservation options show negative costs, which means the curve starts below the x-axis (or, if energy prices are not incorporated in the cost-calculations, their costs are below the costs of the saved energy). The interception point with the x-axis shows the cumulated cost-effective conservation potential and plays a central role in CSC. If CSC are used in energy models to determine investment decisions in certain conservation techniques, all the options up to this intersection point would be implemented and would reduce the resulting energy demand. Generally these curves show a progressive slope, but this may be also due to the fact that the more costly the options become, the less attention they receive; the most expensive options are often not considered at all, while very cost-effective options get a lot of attention from analysts and policy makers.

CSCs are based on the concept of constant individual utility, which means they show the available energy or greenhouse gas savings assuming no change in utility. To translate this concept of constant utility to energy modelling, it is generally assumed that the economic activity related to the energy consumption is not affected and thus remains constant. The economic activity may be the level of useful energy consumed, or the level of production or value added in industry. By keeping the utility constant, all the costs that are related to the energy savings are shown on the CSC.

CSC are comparable to economic supply curves. They show the cumulated energy savings on the x-axis and the marginal costs related to the realisation of these savings on the y-axis. In economic supply curves, the cumulated supply is shown on the x-axis and the marginal costs on the y-axis.

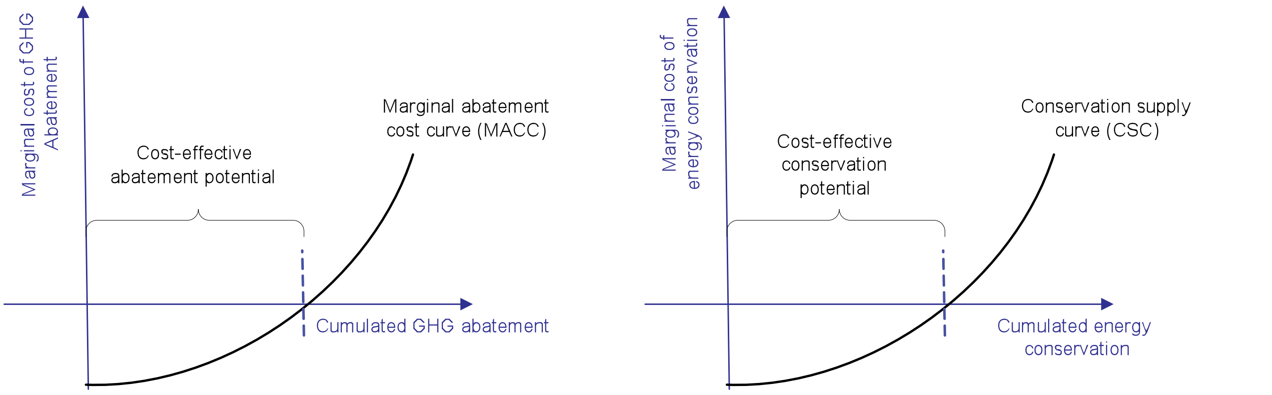

Figure 1. The concept of MACC and CSC

More details about the theoretical background of CSC are presented by Blumstein et al. (1995), who show how to derive a CSC from an economic production function.

An exemplary conservation supply curve for European Industry

MODEL DESCRIPTION

The model applied to calculate the illustrative CSC is from the class of energy system models, which means the calculation is based on technological information about distinct conservation options. Regarding the technological foundation of the model, we distinguish between process-specific technologies and cross-cutting technologies. Blast furnaces in steel making are one example for the former; these are very sector- or even process-specific. In contrast, cross-cutting technologies are widespread over very different industrial sectors. Examples are electric motors or lighting equipment.

For process-specific technologies, the main driver is the projection of physical production (e.g. tonnes of crude steel from blast furnaces). The 40 most energy- and greenhouse gas-intensive processes were considered separately in the model. For each of these processes, the specific energy consumption/GHG emissions and the physical production output are model parameters.

Although cross-cutting technologies are usually smaller, there are huge numbers involved due to their widespread application and so they are responsible for a huge share of industrial electricity consumption. Cross-cutting technologies have to be considered to give as complete picture as possible of industrial energy demand. They are implemented in the model as a share of the total sector's electricity consumption and their main driver is the projected development of value added by industrial sector.

The main parameters for the construction of CSC are the energy savings and their specific costs (CCE), which are plotted against the energy saved in the CSC diagram.

In order to calculate conservation potentials, we assigned conservation options to all of the technologies and end-uses. The conservation options are represented in the model by a specific saving potential (sp) and a market diffusion (D), which states how much of the conservation potential is realised in which year. To calculate an absolute energy saving potential (SP), the activity level of the related technology has to be considered as well (A). The conservation potential is plotted on the x-axis of the conservation supply curve.

$$SP_{C,SO,t,EC} = sp_{C,SO,EC} \frac{D_{C,SO,t} - D_{C,SO,0}}{100} * CF_{C,SO,t,EC} * A_{C,Pr,t}$$

Equation 1. Total saving potential. Indices are: C: country; SO: saving/conservation option; t: year; EC: energy carrier; Pr: process

A correction factor (CF) is introduced to account for interactions between saving options. The definition and calculation of the correction factor is presented in the chapter on "interaction and relation of saving options" below.

The calculation of the cost of conserved energy (CCE) is also based on specific information about the individual conservation options. Relevant variables are the specific investment cost (IC) and the specific running cost (RC) per output unit as well as the lifetime of the conservation option. Further variables are the annuity factor (AF) and the price of the relevant energy carrier. The calculation is related to the calculation of the cost of conserved energy as presented by Velthuijsen (1995, p.6).

$$cce_{C,SO,t} = \frac{IC_{C,SO,t}}{\sum_{EC=1}^{n} sp_{C,SO,EC}} * AF_{C,Se,t} + \frac{RC_{C,SO,t}}{\sum_{EC=1}^{n} sp_{C,SO,EC}} - \frac{\sum_{EC=1}^{n} sp_{C,SO,EC} * PE_{C,t,EC}}{\sum_{EC=1}^{n} sp_{C,So,EC}}$$

Equation 2. Costs of conserved energy

The economic input data for each conservation option were collected as specific values related to the quantity of production. For the construction of CSC these have to be transformed into specific cost values per unit of energy saved. The total specific costs of conserved energy (cce) are calculated as the sum of the specific investment and O&M cost per saving potential (sp) minus the cost savings due to the reduced energy consumption.

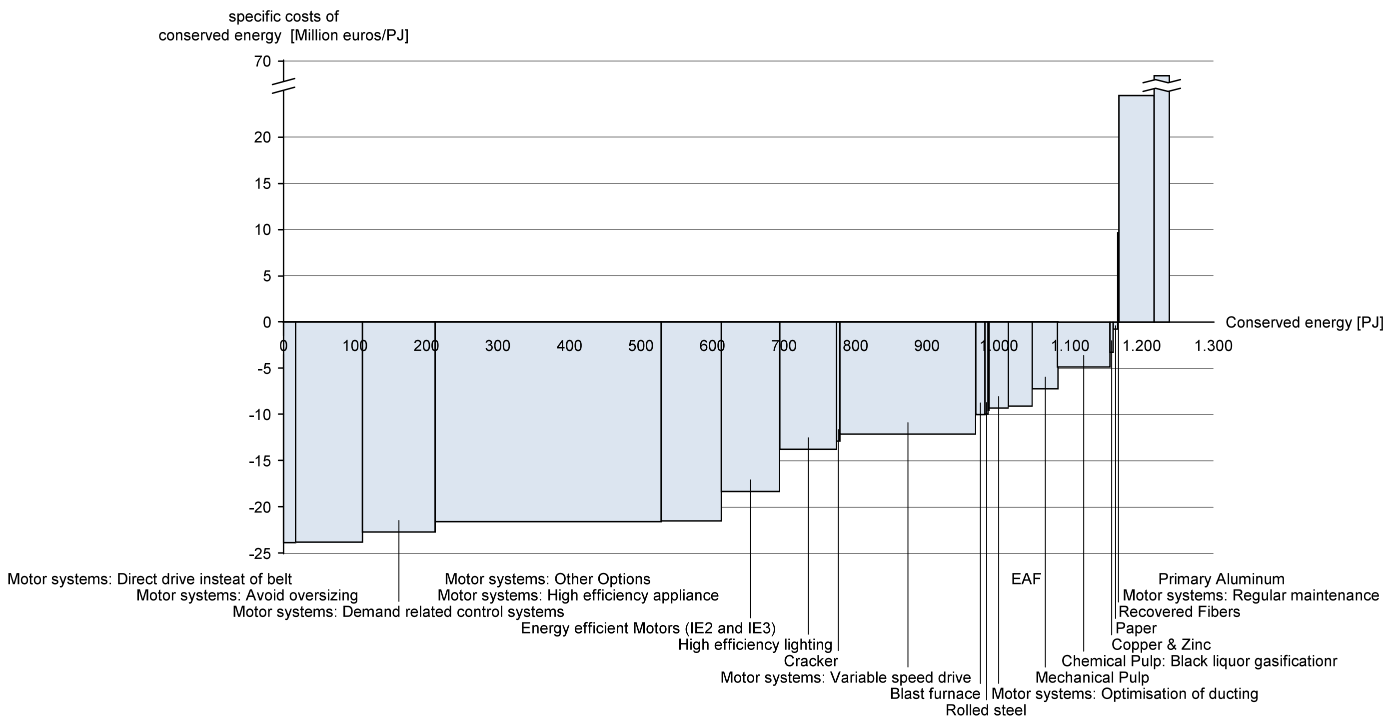

Figure 2. Exemplary CSC for electricity savings in European industry (year: 2030); source: own calculations

The latter also consider varying energy prices and are therefore calculated separately for each energy source.

INPUT DATA

The input data are crucial for the quality of the final CSC. Official statistics are available for some of the exogenous variables that determine the analysed system in the base year, e.g. energy prices, which were taken from IEA publications, and energy consumption by industrial sector in the base year, which was taken from Eurostat databases.

For more specific technological data, values were taken from the literature, expert interviews and estimates based on case studies. The reliability of this data is generally lower than the official statistical data described above.

There are also scenario input data which are to be regarded as sound assumptions of the future development of certain main drivers. They serve to translate the general scenario philosophy into quantitative exogenous inputs. These are mainly projections of industrial production, the value added by industrial sector and the whole set of prices for energy carriers as well as emission certificates. Projections of the GHG intensity of electricity production are included in order to calculate indirect emission abatement as a result of electricity savings. As far as possible, the chosen projections are compatible with the EU energy scenarios.

RESULTS

Figure 2 shows an exemplary CSC for electricity savings in European industry up to the year 2030. The savings are calculated in relation to a "business as usual" development. As mentioned, the steps of the curve represent bundles of distinct conservation options and there is no overlap between the distinct measures (see also chapter on the interaction of saving options). The technological data and the methodology of this curve will be used throughout the document, if not stated otherwise. Only selected methodological issues will be changed to estimate their effect on the results.

Critical assessment of the methodology of conservation supply curves

SENSITIVITY TO EXOGENOUS INPUT VARIABLES

It is not surprising that the input variables have a considerable effect on the results, but a sensitivity analysis gives a better idea of the magnitude of this effect. Main input variables include discount rates for the investment calculation and energy prices as well as emission factors and CO_2 emission certificate prices, which are relevant for MACC.

The discount rates used vary strongly among the different studies assessing the costs and potentials of energy conservation investments. Anderson et al. (2004) analysed several thousand energy conservation projects in US industry and found strongly varying threshold discount rates that were applied to determine investment decisions in energy-efficient technology. They calculated a mean payback time threshold of 1.4 years, which corresponds to a discount rate of approximately 70%. Although discount rate thresholds below 25% were applied in some projects, in about 79%, payback thresholds of less than two years were applied. Also De Canio (1993) found a mean payback expectation of two years among US manufacturing companies. Thus, while the general payback expectations of companies seem to be very ambitious, considerable variation could be observed. These high discount rates which are derived from the payback time criterion implicitly incorporate transaction costs related to the investment into the model.

Consequently, if CSC are to be used in energy modelling as criteria for investment decisions in individual conservation

Table 1. Example showing the influence of power generation's CO2 intensity on the abatement costs

	Country 1	Country 2
Electricity savings due to use of efficient motor	1 MWh/a	1 MWh/a
Financial savings due to conserved electricity	50 €/a	50 €/a
CO_2 intensity of power generation	600 g CO_2/kWh	20 g CO_2/kWh
CO_2 abatement related to the efficient motor	600 kg/a	20 kg/a
Costs of CO_2 abatement	-50 €/ 0.6 t = **-83 €/t**	-50 € / 0.02 t = **-2500 €/t**

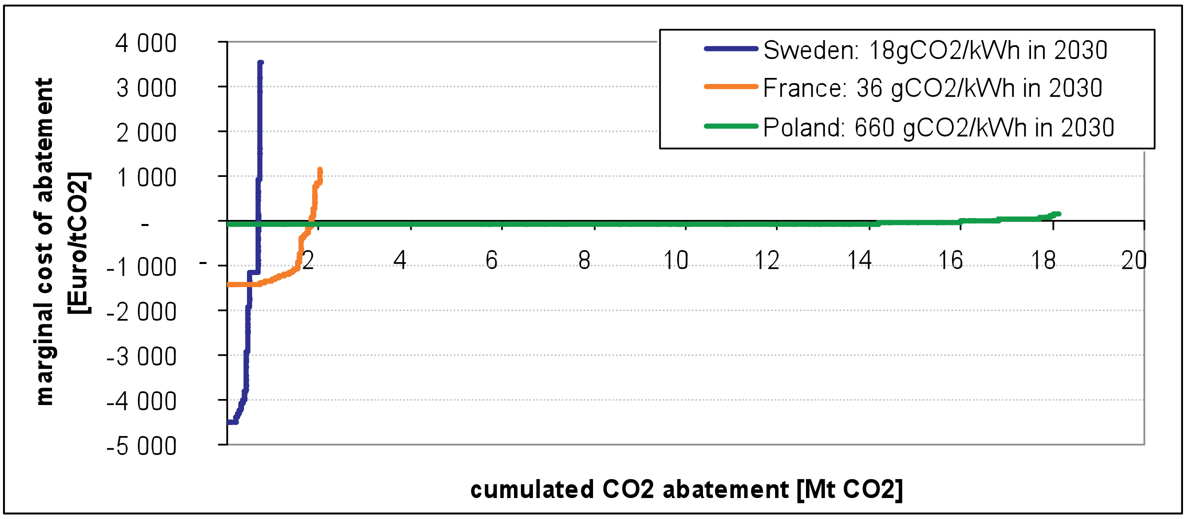

Figure 3. MACC for Sweden, France and Poland in comparison (only indirect CO_2 abatement due to electricity savings shown) source: own calculations

options, a relatively high discount rate seems realistic in the case of industry. But if CSC are used to present the conservation potentials and costs, a lower discount rate is justifiable and mainly a question of the chosen perspective. The discount rate can be lower if the costs for society as a whole are shown, because society faces a lower risk than individual companies which conduct only a limited number of projects. This social discount rate lies below the cost-of-capital discount rate and far below the above mentioned discount rates that also consider transaction costs.

Emission factors, especially indirect emissions from the production of electricity, differ considerably between countries. In the case of positive abatement costs, a country with a higher CO_2 intensity of electricity production faces a larger abatement potential of each individual abatement option and lower specific costs per reduced tonne of CO_2 than a country with lower CO_2 intensity of power generation. Consequently, reducing CO_2 emissions by conserving electricity seems more effective and efficient in a country with CO_2-intensive electricity production. The conclusion is not as simple for the opposite case. If abatement costs are negative, i.e. the abatement option is cost-effective, the MACC advocates abatement in the country with the lowest CO_2 intensity, because the related costs are very low. This is always the case when the abatement option is already cost-effective due to electricity savings; in this case, a low CO_2 intensity results in a much larger amount of energy saved per constant amount of CO_2 abated and thus reduces the costs (see also Table 1 for a simple example).

In other words, the cost curves comparing countries indicate that abatement would be most cost-effective in countries with low carbon-intensive electricity production (e.g. Sweden, France) and more expensive in countries with a coal-based generation mix (e.g. Germany, Poland), as shown in Figure 3.

THE ASSESSMENT OF COSTS AND THE ROLE OF BOUNDARIES

While CSC and MACC show the costs of conserved energy (CCE) or the abatement costs on their y-axes, it is rarely clear how these costs are defined and calculated.

When evaluating energy efficiency investments, an important issue is the differentiation between additional and full costs. Full costs refer to all the direct costs related to an energy efficiency investment. For an energy-efficient electric motor, for example, these costs comprise the motor price and the installation. Additional costs, in contrast, do not consider all the costs involved, but evaluate the energy efficiency investment compared with the investment in standard technology that would have been made instead. In the electric motor example, this means only the price difference between a standard and an energy-efficient motor is taken into account. Thus, the concept of additional costs results in considerably lower costs but also places restrictions on the diffusion of energy-efficient technologies. If the energy efficiency investment is regarded as an alternative investment, it can only take place within the scope of general investment cycles, which are generally relatively long for industrial equipment and facilities. The lifetime of an electric motor may be more than 20 years and so it would take at least 20 years to replace the entire motor stock with energy-efficient motors. Other industrial technologies and facilities have even longer lifetimes (Worrell, Biermans 2005). Therefore, reducing the costs by binding the efficiency investment to the general investment cycle is accompanied by a slower diffusion of energy-efficient technologies.

This shows that the cost assessment is methodologically linked with the diffusion speed of new technologies. Thus, the technologies' lifetime becomes a main variable and determines the results in two ways. First, it is mostly used as a proxy for stock turnover and is thus directly correlated to the diffusion speed of new technologies. Second, it is a main variable in the investment calculations. Bearing in mind this high importance of the technologies' lifetime, it seems astonishing that this is often included in the models by a general rule of thumb and that empirical studies are only rarely conducted. Worrell et al. (2005) analysed the case of electric arc furnaces for aluminium production and found that the age of the retired electric arc furnace plants varied considerably between 1 and 47 years in the USA. Although most furnaces were retired in the interval between 10 and 30 years, this still leaves a lot of uncertainty and might bias the results. Taking 10 years instead of 30 years as the value for stock turnover would, (very) roughly estimated, triple the annual costs and the diffusion speed of new plants. The general underestimation of the importance of technologies' lifetime for cost calculations is also shown by the fact that many studies include sensitivity calculations for (comparably low) changes in energy prices, whereas the uncertainty of lifetime estimations is actually often even higher.

Another methodological aspect for the cost assessment is the issue of external costs and whether they are considered in the modelling. The existence of external costs and benefits, i.e. costs incurred or benefits enjoyed by third parties not directly involved in the economic activity, has often been proved. Whether to consider external costs and benefits when constructing CSC is merely a question of the chosen perspective. If the perspective is that of the decision maker (i.e. the firm or the private person investing), external costs are not considered as they generally do not influence the decision. If the CSC is constructed to show the costs for society, external costs and benefits can be incorporated. The influence of energy conservation and abatement of GHG emissions on external costs are mostly related to the reduction of pollution.

As discussed above, CSC are usually constructed to only allow conservation options that do not influence the utility for the user compared to a standard technology. So CSC show energy savings that can be realised while not influencing the user's utility. This concept is important in order to exclude all the conservation options associated with a reduction of consumption or production and thus probably utility. To apply the concept of constant utility in CSC, this is often assured by keeping the level of energy service constant. Although all conservation options with a constant level of energy service also have a constant level of utility, this relation does not hold for the reverse; options with a lower or higher level of energy service might well have the same level of utility. Thus, the applied concept of a constant level of energy service excludes options that might be taken into account under the premise of constant utility.

However, in practice, even the concept of constant energy service is hard to ensure and a strict application would actually exclude many of the most important conservation options. Deviations from constant utility are possible in both directions. Examples for very relevant energy conservation options can be given that actually reduce the level of energy service and possibly also utility, e.g. an energy saving lamp which takes longer to start than a standard light bulb. In general, there are very few examples of conservation options that reduce the level of energy service in the literature; most, like the energy-efficient lamp, only have a marginal effect on the energy service level. Options that considerably reduce utility are generally not taken into account in CSC analyses. These are excluded by the definition of energy efficiency, which aims at reducing energy demand but not the level of consumption or production. Most CSC analyses pragmatically take important conservation options into account even though they might have a (slight) effect on utility. This effect is usually not quantified.

In contrast, more examples are discussed in the literature that actually increase the level of utility. The increase in utility is referred to as the co-benefits or ancillary benefits of energy conservation. For example, Worrell et al. (2003) conducted a comprehensive study on the ancillary benefits of energy conservation in the iron and steel industry. The ancillary benefits found were often related to a reduction of production waste, reduced material consumption, lower maintenance needs, lower emissions or improved reliability. By monetising these effects and considering them in the CSC, they found that the cost-effective conservation potential in the iron and steel industry doubled due to co-benefits (see also Figure 4). A comparable study by Lung et al. (2005) analysed the co-benefits of 81 energy efficiency projects in US industry. They found co-benefits in 51 projects many of which only became cost-effective due to the co-benefits.

However, in many cases, monetisation is difficult and subject to considerable uncertainties. Jakob (2006), for example, evaluated the co-benefits from energy efficiency measures in the private housing sector, where these are mostly not expressed in monetary terms. Effects like improved thermal comfort or reduced noise pollution had to be quantified, for example by using empirical data on the correlation of rent losses due to increasing noise pollution.

The cited studies clearly show the importance of considering co-benefits when analysing the costs of energy conservation despite the difficulties related to their quantification. Consequently, CSC that do not take co-benefits into account tend to considerably overestimate the costs of energy efficiency and thus systematically underestimate the cost-effective saving potential – especially in the industrial sector.

Another factor that influences the cost results of the CSC significantly is the often observed reduction of unit cost of new technologies due to experience and scale effects. Especially when the CSC is used for a long-term analysis the effect of cost-degression has to be considered. Unfortunately assessments of cost degression of demand side energy technologies are rare; most studies concentrate on supply side energy technologies like renewable energies. Duke et al. (1999) for example found a learning rate of 11 percent for electronic ballasts of fluorescent lamps (USA in the period from 1986-97, market price in relation to cumulated sales). This means that the price per product decreases by 11 percent for every doubling of the cumulated sales. Especially for emerging energy efficient technologies that still have a low market share and a high potential for learning and scale effects, future cost reductions have to be considered

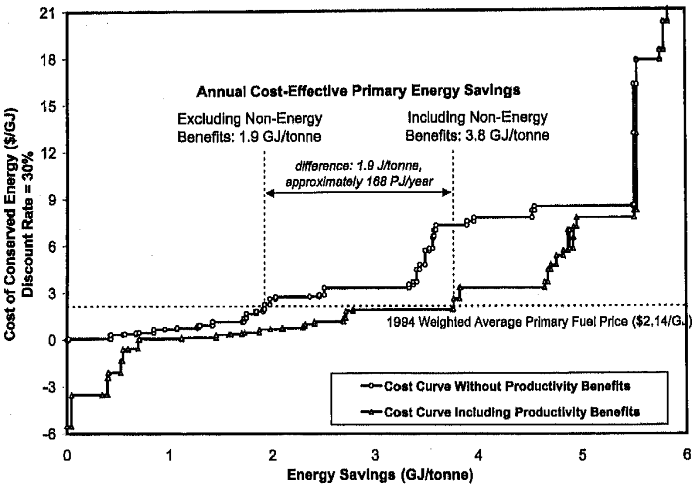

Figure 4. CSC considering co-benefits for the US iron and steel industry (source: Worrell et al. 2003)

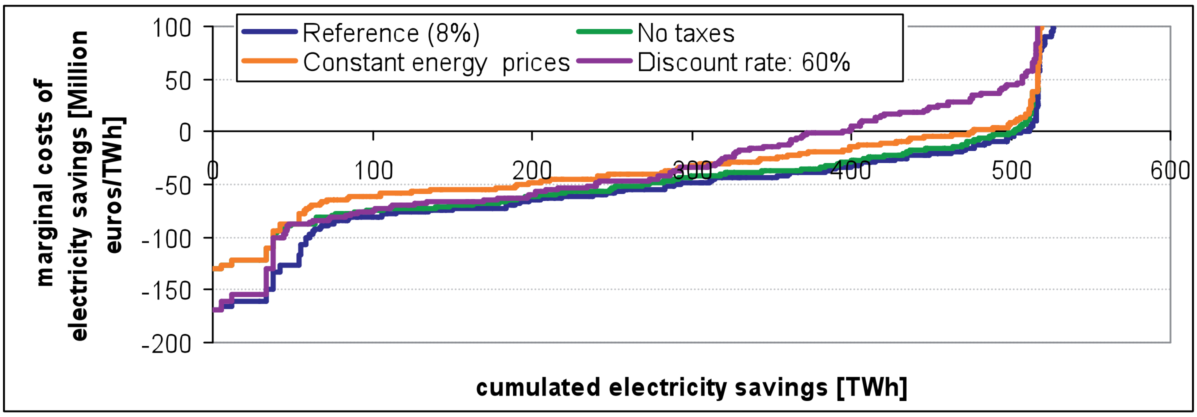

Figure 5. CSC with varying assumptions on cost calculations (EU Industry; year 2030); source: own calculations

when constructing a CSC. Thus, not to consider cost-degression effects for emerging energy efficient technologies in CSC analyses with a long time horizon does produce results with a significant deviation from reality. However, the current empirical basis on cost-degression of demand side energy efficient technologies does not allow to comprehensively including cost-degression in the calculations.

To get a rough idea about the cost degression potential of different types of technologies, it is helpful to look at the technology-classification of Neij (1998, p.3). She differentiates three classes of technologies. The first category comprises whole plants and factories, where the potential for cost degression is very low due to their individual construction. The second category considers so called modular technologies, which can be produced by mass production (learning rate 5 to 30 percent). The third class contains mostly continuous processes from the chemical industry (learning rate 10 to 36 percent). Thus a classification by type of technology allows for a very first estimate of the magnitude of possible cost reductions due to learning and scale effects. Given the huge number of energy demand technologies it seems promising to further work on this classification. The classification of industrial technologies would provide a first basis for the integration of cost-degression effects in industrial CSC.

Figure 5 shows the discussed issues on the CSC. A higher discount rate generally increases the slope of the curve, thus it has relatively low effect at the left side of the curve and stronger effects on the right side. Lower energy prices lead to a vertical upwards shift of the curve and taxes also lead to an upward shift, depending on the tax level of the relevant country.

DEFINITION OF CONSERVATION OPTIONS AND HETEROGENEITY

An often criticised weakness of CSC is their stepwise character, caused by the very common application of average values for all kinds of inputs. In reality, energy carrier prices are depending on the region, the structure of the market, bargaining power, the energy provider, the quantity bought, the energy taxes, the time or the season or in the case of electricity even the connection power. Similar factors also determine the costs of a conservation option that is realised in a certain company. In general large companies might be able to negotiate cost reductions due to larger orders. Furthermore, the conservation potential of a certain technique depends strongly on the very specific technological characteristics of each company. As shown above, the lifetime of conservation options plays a central role in the cost assessment but it is far from uniform between companies; some might replace equipment relatively early while others might even repair and retrofit it several times. These random examples show: reality is heterogeneous, while the models assume an "average world".

Consequently, working with average values in the construction of CSC is a strong deviation from reality and the resulting stepwise investment decisions might alter the modelling results considerably especially when large conservation options have costs close to zero. Verdonck et al. (1998) underline the importance of market niches and that emerging technologies enter the market gradually instead of instantly to their full extent as it is assumed in some CSC. But, although the consideration of heterogeneity is desirable, it is quite a difficult task that complicates the modelling work considerably, demands more computation time and a lot more input data. Having in mind that data requirements of standard energy system models based on average values are already demanding and huge data requirements are often mentioned as the disadvantage of this type of modelling, the extension to ranges and distributions intensifies data requirements even more. A possible approach to improve the method of average prices and stepwise CSC is described by Willemé (2003). In order to consider a wide range of unit cost, he works with logistic curves instead of step-functions to produce a CSC. Another approach, which follows the theory of evolutionary modelling of investment decisions, is followed by Mulder (2005, p.65). He includes heterogeneity in the modelling by assuming a normal distribution for the benefits firms receive from implementing conservation options, but applies his model only to a theoretical example of one conservation option. Blok et al. (2004) introduced heterogeneity by implementing a distribution function for the discount rate, which is used to determine the cost-effectiveness of the energy conservation investment. Also the field of agent based modelling provides promising approaches to consider heterogeneity in technology diffusion models, as for example presented by Wittmann (2008). These examples show that many approaches exist to introduce heterogeneity in the construction of CSC and they should definitely being elaborated further.

However, while the consideration of heterogeneity is inevitable when the CSC is used to simulate investment decisions in the course of energy modelling, this is not so much the case when the CSC is used as an instrument to visualise and compare policy options in the debate about energy conservation and climate protection. In this case, a stepwise curve might make it easier for the reader to differentiate between the distinct options and for the reader it is obvious that real life behaviour is not as stepwise as the curve indicates.

In the case of a stepwise curve, the choice and the definition of distinct conservation options or bundles of conservation options affect on the results. Particularly when many options are combined to one large bundle the impacts might be huge and the curve might seem completely different.

Another important and often not considered factor is the rebound effect. The rebound effect describes the increase in energy consumption as a direct consequence of cost savings due to energy conservation. Bentzen (2004) estimated the rebound effect for the US manufacturing industry over a 50 year time period with 24% as upper bound. Greening et al. (2000, p.396) found a short term rebound effect of 0 to 20% for industrial process uses. Although there is a wide range of empirically derived rates, the order of magnitude indicates the substantial effect the rebound effect might have on the resulting energy consumption and ignoring the rebound effect in the construction of CSC leads to overestimated saving potentials. However, to account for the rebound effect in the CSC calculation is more complicate than thought at first glance; the rebound effect can not simply be subtracted from the conservation potential, because the rebound comes along with a rise in the energy service level, which is contradicting the general assumption of constant utility in CSC. For a possible approach to account for this utility increase while considering the rebound it is referred to Stoft (1995, p.128).

As already shown, a crucial factor for the construction of CSC is the conservation potential of the individual conservation options. In many studies it is not transparent which "potential" they mean and how it is defined and calculated. The simplest approach is to define the conservation potential as the difference in a technique's energy consumption after an energy efficiency improvement as compared to before the improvement. This approach shows the savings as difference between a technical conservation potential and a frozen efficiency baseline. While this is a pragmatic and transparent approach, it is not sufficient if the CSC shall show the conservation potential that is available to energy efficiency policies and measures, because it would implicitly assume that the whole conservation potential is available to energy policy. Therefore analysts try to consider an "autonomous improvement baseline", which shall account for an energy efficiency improvement that would have taken place without the policies, instead of the "frozen efficiency baseline". Although methodologically correct, this approach obviously comes along with a major new problem: "determining what would have happened (some twenty years in the future) without these programmes" (Stoft 1995, p.130). Thus, there is no best approach to the problem of defining the conservation potential, but this even more underlines the importance of transparent assumptions, because the difference in the results might be huge.

Another factor is related to the core methodology of bottom-up energy models and the construction of CSC from distinct conservation options. To construct CSC mostly the described bottom-up approach is applied, in which every single technology option has to be assessed and distinctly included in the calculations; it is obvious that further conservation options do always exist, given the enormous complexity of the industrial production system. Particularly in the longer term when more and more new options become available that are not known initially and thus cannot be predicted. Therefore, the resulting potentials are to be interpreted as showing a possible efficiency improvement for a certain well defined set of conservation options, but additional options that might change the slope of the CSC always exist.

PATH DEPENDENCY

Although it is possible to construct CSC without the consideration of time, or in better words, for instant conservation of energy, in most cases and for all energy and climate modelling applications the CSC are constructed for a certain time period. The huge importance and influence of the time horizon is already shown in the chapter on cost issues. Not so widely acknowledged is the fact that not only the final year of the calculations matters, but also the path towards this year.

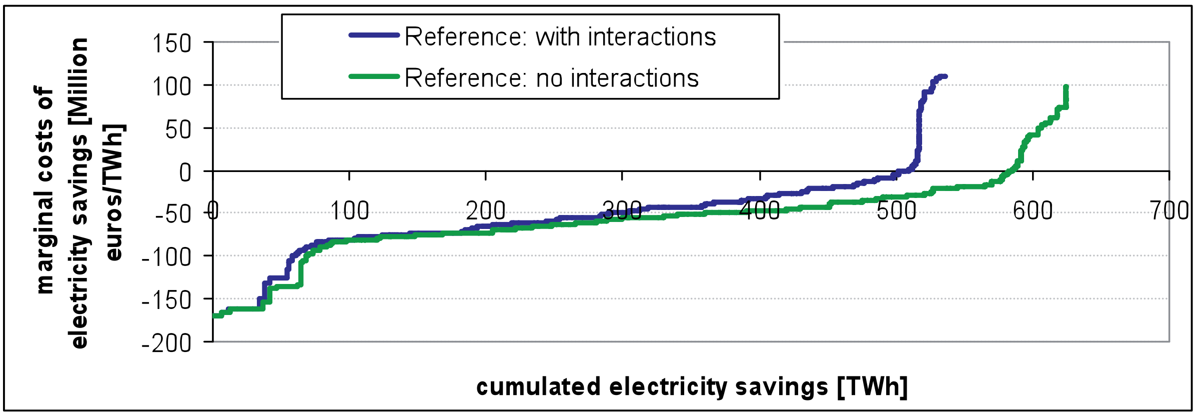

Figure 6. CSC with and without consideration of interactions between conservation options (EU-industry; year 2030) source: own calculations

In our presented model the costs of conservation options were given for each analysed year and thus a reduction of costs over time can theoretically be implemented for chosen new technologies. According to Equation 2, the calculation of the cost of conserved energy in year t is determined by the technologies' investment cost in year t and then related to the whole conservation potential (as a product of the technology's diffusion and conservation potential). While this is a practical modelling approach, in the case of considerably decreasing unit costs it does not represent reality adequately, because most of the technology diffusion in year t took place in the previous years, in which the conservation technology might have been considerably more expensive. Therefore our approach either does not allow considering decreasing costs as a result of economies of scale and economies of experience or it underestimates the investment costs. To avoid these shortcomings a model has to memorise the diffusion path and build a technology stock. The technology stock then allows allocating the unit costs of each past year to the relevant investment of that year and thus considers past costs in the assessment of the cost of conserved energy in year t.

INTERACTION AND RELATION BETWEEN CONSERVATION OPTIONS

As a matter of fact, most conservation options are not independent but influence each other. This interaction always occurs, when several conservation options are related to the same energy flow. The example of a ventilation system will illustrate this effect. Assuming that the use energy in terms of air volume flow remains constant, energy can be saved by for example replacing the fan by a more efficient one or by optimising the air flow in the pipe system and thus reducing flow resistance. If now, the pipe system is optimised first, this will also reduce the losses occurring in the fan itself, because less power is needed to provide the same air volume flow. Consequently, the remaining saving potential for the replacement of the fan is lower than before optimising the pipe system. If the optimisation of the pipe system saved 20 percent of energy consumption, also the remaining saving potential for the replacement of the fan is reduced by 20 percent. Verdonck et al. (1998, p.17) also mention the case of mutually exclusive options like double pane windows and triple pane windows.

Thus it is indispensable to consider these technical interactions in the construction of a CSC; otherwise the CSC would only show a comparison of independent and alternative conservation options but would not allow showing the marginal costs of conservation for a chosen quantity of energy saved.

For most cases, there is no interaction between options, when the options are related to different energy flows. For instance the replacement of a conventional light bulb by a fluorescent lamp has no influence on the conservation potential of using a high efficient electric motor in a compressed air system. The energy flow through the compressed air system is not related to the energy flow through the lighting system, at least if the relevant energy flow is assumed to begin with the provided electricity at the user site, meaning that generation and transmission of electricity is excluded. One often cited example for interactions across energy-flows is the inefficient light bulb that reduces the energy used for fuel based space heating.

From a methodological point of view, the question is how to consider the interactions when constructing the CSC. Stoft (1995, p.112) followed the approach of predefining a certain order for the realisation of conservation options. Among all options that are related to the same energy flow, he chooses the most cost-effective one, which then is realised on top of a given base case and is not influenced by any of the other options. Then he recalculates the new energy consumption corrected by the achieved savings with the first option and applies a second option, which is the most cost-effective one among the remaining options, on top of the new energy consumption. This algorithm is followed until all options are calculated. The application of this least-cost algorithm makes options, which are already relatively expensive, even more expensive and does not or only marginally affect the most cost-effective options. While this algorithm is in line with the least-cost methodology of CSCs, it might be in conflict with real world behaviour, where technical restrictions exist. For example in a compressed air system, replacing an electric motor might be the most economical option, but it might not make sense to replace the motor first, while other options exist that will reduce the demand for rotational energy and thus allow for a smaller motor size. For the construction of a CSC these technical restrictions can only be considered by predefining certain sets of conservation

Table 2. Summary of determinants and their impact on the CSC

	Effect on conservation potential	Effect on specific cost of conservation
Input values		
Quality of input data	Both directions	Both directions
Higher discount rate	-	Higher
Higher energy prices	-	Lower
Longer technology lifetime	Lower: Slower diffusion of efficient technologies through the stock	Lower investment costs due to longer use of technologies
Technology data	Both directions	Both directions
Stronger growth in activity variables (production, value added)	Increasing absolute potential	-
Methodology – decisions		
Consider energy taxes (not VAT)	-	Higher
Considering heterogeneity	Both directions	Both directions
Relate conservation potential to an autonomous baseline development	Lower	-
Considering non-monetary costs	-	Higher
Additional instead of full cost assessment	Lower: Slower diffusion of efficient technologies through the stock	Considerably lower
Grouping of distinct options	Both directions	-
Considering external costs	-	Mostly lower costs due to reduced external costs (pollution), some options with higher costs
Methodology - deficiencies / shortcomings		
Considering interactions of conservation options	Considerably lower	Higher (for most options)
Scale and learning effects	-	Lower costs (in the long term)
Rebound effect	Overestimation of conservation potential	Higher
Considering co-benefits	-	Considerably lower costs
Omission of conservation options	Higher	Higher

options in chosen cases where the technical reality would be violated otherwise.

Figure 6 illustrates the effect of considering or omitting interactions between conservation options. The diagram clearly shows how the cost-effective conservation potential is reduced due to the consideration of interactions.

SUMMARY

Table 2 shows a summary of the discussed determinants and their influence on the conservation potential and the costs of conservation. The determinants are divided into three main groups. The first describes all the effects associated with the input data. This includes mainly variables estimated to describe a certain scenario development. The second group covers methodological decisions that depend on the goal of the CSC. For example, energy taxes should not be included if the perspective is that of society as a whole, instead maybe external costs should be considered in this case. Heterogeneity and non-monetary costs (transaction costs) should be included if the CSC is used to model energy demand projections. The third group refers to methodological issues that represent clear shortcomings if not considered. They do not depend on the perspective chosen, but do occur and need to be considered.

To get an idea of the enormous influence these factors have on the final CSC, we calculated two CSC with opposite assumptions for some of the above factors. The results are illustrated in Figure 7. For the low and expensive CSC, we assumed a discount rate of 60%, constant energy prices based on the prices of 2007. Energy taxes were not considered, nor was growth in GDP as a main driver of energy demand, and only savings above a baseline were taken into account which represents autonomous energy efficiency improvement.

For the high and cheap CSC we took a discount rate of 8%, and rising energy prices according to the EU reference scenarios on energy demand development from 2007; we considered energy taxes and a growth in GDP comparable to the mentioned EU scenario, as a baseline we considered a "frozen efficiency" development and we did not allow for interactions between conservation options.

The resulting CSC are totally different: One indicates a cost-effective annual saving potential of 600 TWh, while the other is less than 200 TWh, even though there were no changes in the technological data and the number of considered conservation options is the same in both cases. The difference between these curves would even be a lot greater if additional factors from Table 2 were taken into account.

Conclusions

The assessment shows clearly that the determinants influence the saving potential and the costs of conserved energy in both directions. A general statement to the effect that CSC always under- or overestimate the costs of conserving energy or abating GHG cannot be made. Instead this paper showed that, in order to correctly interpret certain CSC and MACC, it is necessary to be informed about all the methodological assumptions

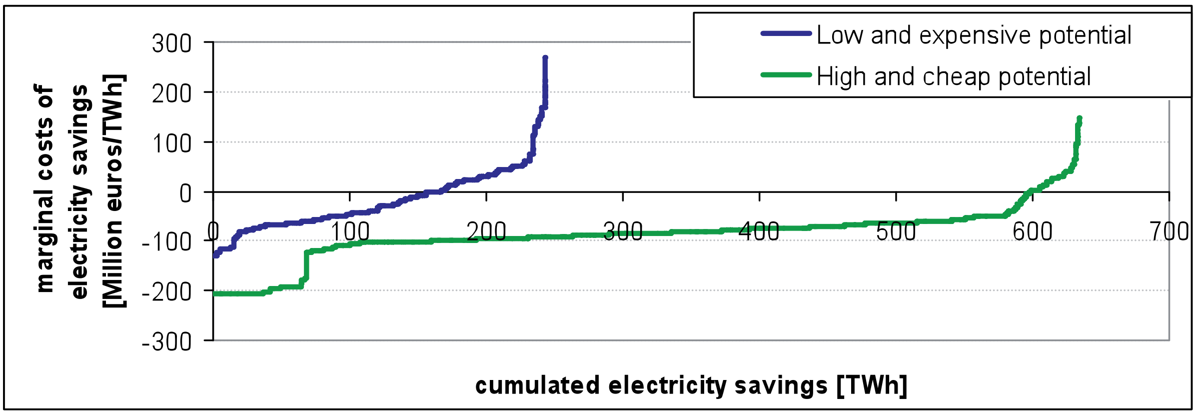

Figure 7. Comparing two CSC with opposite assumptions but the same technological data (EU industry, year 2030); source: own calculations

and the order of magnitude of the possible effects on the results, or at least the direction in which they influence the results.

Beyond purely methodological assumptions, there are certain methodological issues which represent clear shortcomings if not considered, e.g. the interactions between conservation options, scale and learning effects, rebound effects, co-benefits and the omission of conservation options. For all these issues, the methodological background to implementing them in the calculation algorithm of CSC is known and has been discussed in several other papers, only the weak empirical basis is a crucial restriction. Most of these effects simply cannot be considered for many demand-side energy-efficient technologies due to the fact that no data or knowledge is available.

Despite these shortcomings and the methodological problems discussed, CSC and MACC are powerful tools and will remain so for energy analysis. They will also continue to play a central role in energy and climate policy models. To take full advantage of their potential, however, a thorough documentation of the applied assumptions is indispensable and a wider and more reliable empirical basis would significantly improve the quality of future CSC. Only if comprehensive empirical data are available, for instance on the rebound effect or the cost-degression of energy-efficient industrial technologies, can energy demand models incorporate these factors into the calculation of CSC and overcome some of the main shortcomings discussed in this paper.

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