On the problem of optimizing through least cost per unit, when costs are negative: Implications for cost curves and the definition of economic efficiency.

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Abstract

For society and industry alike, efficient allocation of resources is crucial. Numerous tools are available that in different ways rank available options and actions under the aim to minimize costs or maximize profit. One common definition of economic efficiency is least cost per unit supplied. A definition that becomes problematic if cost take negative values. One model, where negative costs are not uncommon, is expert based/bottom up [marginal abatement] cost curves. This model is used in many contexts for understanding the impact of economic policy as well as optimizing amongst potential actions. Within this context attention has been turned towards the ranking problem when costs are negative.

This article contributes by widening the discussion on the ranking problem from the MACC context to the general definition of least cost per unit supplied. Further it discuss why a proposed solution to the ranking problem, Pareto optimization, is not a good solution when available options are interdependent. This has particular consequences for the context of energy systems, where strong interdependencies between available options and actions are common. The third contribution is a proposed solution to solve the ranking problem and thus how to define economic efficient when costs are negative.

Keywords: Economic Efficiency; Marginal Abatement Cost Curves; Investment Optimization; Policy Analysis

1 Introduction

Organizing and allocating resources is essential for developing, and potentially sustaining, our modern society. However, it is a complex and often problematic task, a task that society, industry and individuals must manage in the best possible manner. If not there is a risk that welfare, dividends and wealth fall short of their potential (Pigou, 1920).

During the 1970s, the combination of the oil crises and improved computational capabilities created a demand for new models to quantify the effect of changes on energy systems and the economic performance of energy markets (Weijermars et al., 2012). Originating from a dissertation by Meier (1982), an iterative bottom-up optimization model called conservation supply curves (CSC) was developed during this era. The aim was an analytical methodology to provide a solution to the questions of was it more economical to invest in energy efficiency or build new electric power production capacity, and how to prioritize between different available options. The model is used today for many different applications (besides energy conservation) by firms, governments and NGOs such as the International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC) and World Bank.

The CSC model is based on the partial equilibrium (PE) model. The supply and demand curves of PE are one of the most basic models used in economics. CSC differs from PE in how the supply curve is generated. Instead of the traditional smooth curves generated through economic models, the performance of discrete actions is estimated, such as adopting certain technologies, to estimate the supply curve. With price as marginal cost per additional kWh on y-axis and the quantity of kWh on the x-axis, CSC allows the calculation of supply and demand through a set of such discrete available options. As a result, instead of the smooth supply curves generated through economic models, CSC's "supply" curve instead consists of a sequence of boxes corresponding to calculations or estimations of each considered action (see Figure 1). This has been referred to as expert-based or bottom-up estimations in the literature (Taylor, 2012; Kesicki and Stranchan, 2011).

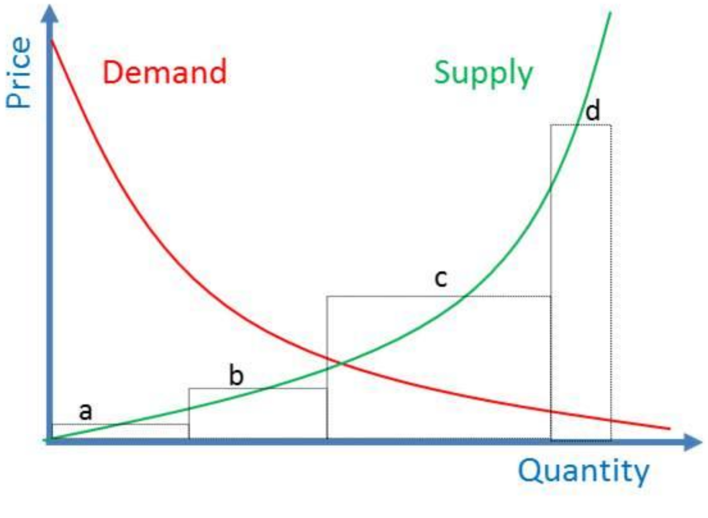


Figure 1. In CSC, the "supply curve" is estimated through analyzing the effect of adopting discrete options, corresponding to the boxes **a-d**. In this example, adopting option **a** and **b** would almost meet the demand.

In essence this is a bottom-up least cost integrated planning approach (Vine and Harris, 1990) with the aim of understanding the effect of discrete actions. Such an approach establishes a merit between a set of available options in the CSC model through least cost per unit(s) supplied.

During 1990s, the CSC model was transformed to fit a climate change context in the form of marginal abatement cost curve (MACC) by Jackson (1991). As noted by Taylor (2012), Ward (2014) and Wallis (1992a; 1992b), the application of this bottom-up or expert-based optimization approach is problematic when considering actions with a negative marginal cost.

The metric problem of the CSC/MACC model, when options with a negative marginal cost are considered, is simply illustrated with the following example from the climate change context. Consider that a firm has three different investment options that would reduce CO_2 emissions and reduce costs (Table 1). In practice, many options that both increase productivity and reduce CO_2 emissions are similar to this logic. Option A has a marginal cost (MC) of -10 and "supply" the quantity of 5 units of CO_2 abatement (marginal abatement, MA = 5); option B has a MC of -15 and MA of 10; and option C has an MC of -10 and a MA of 1.

Table 1
Option A, B and C used to exemplify the optimization problem of expert-based least cost integrated planning through the partial equilibrium-based CSC/MACC model.

Option	MC	MA	MAC (MC/MA)
A	-10	5	-2
B	-15	10	-1.5
C	-10	1	-10

Common sense dictates that we should prioritize the allocation of resources to the option with the highest financial return (lowest MC), which also supplies most CO_2 emissions reductions (highest MA). In this case option B reduces cost and emissions the most. Option A and C reduce the cost equally, but A reduces CO_2 emissions more than C, which is why it is the better option of the two. The result is an optimal prioritization sequence of B-A-C.

If we use the metric of the partial equilibrium model (as well as in present CSC/MACC), that is least cost per unit supplied, we get another result though. Defined as marginal abatement cost (MAC), in other words cost per unit in the form of MC divided with MA, option C would seem to be the better option with a MAC of -10. Second in merit we would find option A at an MAC of -2, while least in merit we would find option B with an MAC of -1.5. Although, as I previously discussed, option B is the best option financially and in terms of climate change abatement. This is a potential problem for all optimizations where least cost per unit supplied is used as a metric, when costs could take negative values. The problem is thus not limited to the context of CSC/MACC.

This is an easily spotted problem in both corporate and scientific derived CSC/MACCs, once awareness is raised. The area of the boxes corresponds to the MC, the width along the x-axis to MA. Wider boxes with a larger area thus correspond to better options than narrower bars with a smaller area, although such merit is not used in the present CSCs/MACCs.

One example of a biased conclusion made through the faulty ranking is found in the research by Fleiter et al. (2009), who concluded that it would be more economically efficient to reduce CO_2 emissions in low carbon economies such as Sweden than in high carbon economies such as Poland. Using common sense similar to the example in Table 1, looking at least cost and largest effect on reducing emissions, and thus managing the ranking problem, their result would prove the opposite. Some other examples of this error are the curves by the consultancy firm McKinsey & Company, in reports such as their "Global abatement cost curve 2.1" (McKinsey & Company, 2010). Here, one example is the emphasis on substituting present illumination with the LED technology, which gives a considerably small desired supply through small cost reductions. Other options such as plug-in hybrid vehicles and improving efficiency in industrial processes has much larger cost reductions and supply, but are ranked as less economically efficient than LED.

Many research articles apply CSC/MACC. Some examples showing the spread in application of the model and biased ranking include the following: Nackicenovic and John (1991), who used CSC and MACC to analyze worldwide CO_2 abatement strategies. Morthorst (1994) used MACC to conclude that it was possible for Denmark to reduce CO_2 emissions without inflicting a significant economic burden. Halsnaes et al. (1994) and Halsnaes (2002) used MACC to analyze the difference in abatement costs between different nations and abatement actions. Mirasgedis et al. (2004) and Georgopoulou et al. (2006) used MACC to evaluate different policies to reduce CO_2 emissions in Greece. Flachsland et al. (2011) used MACC to analyze the effect of including road transport in the EU Emissions Trading Scheme (ETS). Nordrum et al. (2011) used MACC to assess the potential of different options and corresponding costs for the petroleum industry in California, while Murphy and Jaccard (2011) analyzed the results generated by McKinsey & Company for the US.

The problem of ranking options with negative marginal cost was already identified in research in 1992 by Wallis (1992a, 1992b), but not as a methodological argument. The notion of the problem by Wallis was part of a larger discussion and the scientific community does not seem to have taken notice of its methodological implications.

In 2012, Taylor (2012) raised the problem again. Taylor proposed avoiding the optimization problem by utilizing Pareto optimization instead. The thought of Pareto optimization is to establish what options are Pareto optimal. In this case it is the set of options, where a shift between options cannot improve either MC or MA without reducing the other. Pareto optimization is problematic though in relation to energy systems and does not solve the metric problem, as will be argued for later.

Still, MACCs/CSCs with the problematic optimization continue to be published in articles in high ranked journals, as well as an increasing number of corporate reports that utilize the model. Amongst the recent research articles we find Dedinec et al. (2013) with abatement in the Macedonian transport sector; Wächter, (2013) with abatement strategies for Austria; Yang et al. (2013) with abatement from the cement industry in China; and Garg et al. (2014) with abatement related to electric power production emissions in India. Other recent examples include analyses of efficiency improvement potential for the United States petroleum refining industry (Morrow et al, 2015) and the potential to reduce CO_2 from maritime shipping (Yuan et al, 2016).

In the IPCC's 2014 report AR5, MACC was presented as one tool to analyze climate change mitigation (IPCC, 2014). According to the IPCC, MACC is one of the three major approaches to understanding the economics of climate change mitigation, together with CSC (using the name Energy Supply Cost Curve in the report) and integrated modelling. The IPCC generated scenarios in the report are based on the last approach, which is based on input from different cost curves though. Being a synthesis report, many of the included articles also rely on reports with MACCs with the faulty ranking. The impact of this bias is unknown.

When screening MACCs in journal articles, only a few articles since 2012 have taken the problem with ranking negative cost options into consideration — two are co-authored by Simon Taylor (Ibn-Mohammed et al., 2013; Ibn-Mohammed et al., 2014). An article by Hamamoto (2013) has circumnavigated the problem, however, seemingly unaware of its existence. There is one earlier article by Moran et al. (2011) that has deliberately managed the ranking problem, but they do not elaborate on the problem or the consequences of their solution.

In 2014, Ward (2014) published a short communication about the problem, seemingly unaware of Taylor's 2012 article. According to Ward, MACCs should never be used in its present form to rank options with a negative marginal cost. He promotes the idea to introduce a value on avoided CO_2 emissions reductions of different options to establish which are the most effective. Furthermore, Ward expresses the need to urgently address the optimization problematic of the model. This is important given the widespread use of the model and its importance to the climate change abatement context. The articles by Ward and Taylor was recently highlighted in a review of the MACC-model by Huang et al (2016).

This article has three main contributions. The first is widening the discussion of the ranking problem and its consequences. The second contribution is a discussion of why Pareto optimization is problematic in relation to energy systems. The third and last contribution is suggesting a solution to the ranking problem and thus how to define economic efficiency in relation to negative costs.

2 Background

Organizations face many challenges. The 1970s provided no exception, as the world was struck by two oil crises, which skyrocketed energy prices. To find the most efficient means to increase the amount of available electricity in the US markets, the optimization model of CSC was developed at the Lawrence Berkley National Laboratory, which resulted in a PhD dissertation by Meier in 1982 (Meier, 1982), and an article by Meier, Rosenfeld and Wright (Meier et al, 1982) in *Energy* the same year (a conversation with Rosenfeld about the models origin is presented in Stoft, 1995). Inspired by the partial equilibrium model of supply and demand, the idea was to estimate which energy conserving actions were economically favorable and how much electricity would be made available by investing in them. The goal was to determine which options had the lowest cost per additional kWh. In other words, which investments were most economically efficient with the aim of creating the "supply curve" for making extra kWh of electricity available to the market.

In his work, Meier (1982) provided a derivation of the optimization capabilities of the model and provided some examples of its application. It should be noted that Meier's analysis only included options with positive marginal cost. During the 1980s, these curves became a popular tool and were widely used within the energy conservation context, especially in the US (Wallis, 1992a).

Simplified, the model was designed to calculate the cost of conserved energy (CCE) per unit conserved and the conservation potential of all the options. The option with the lowest CCE per unit was then selected after the CCE was recalculated for the remaining conservation options under the assumption that the first option had been selected. From the remaining options, the one with lowest CCE was selected and then the iteration continued. Thus, a supply curve is determined for which information is revealed and which options are economical to implement given certain market prices for electricity, and how the implementation of these options should be prioritized. Furthermore, the model allows the analysis of how the market price for electricity affects the rationale of considered energy conservation options. In 1995, Blumstein et al. (1995) derived the CSC model from an economic production function.

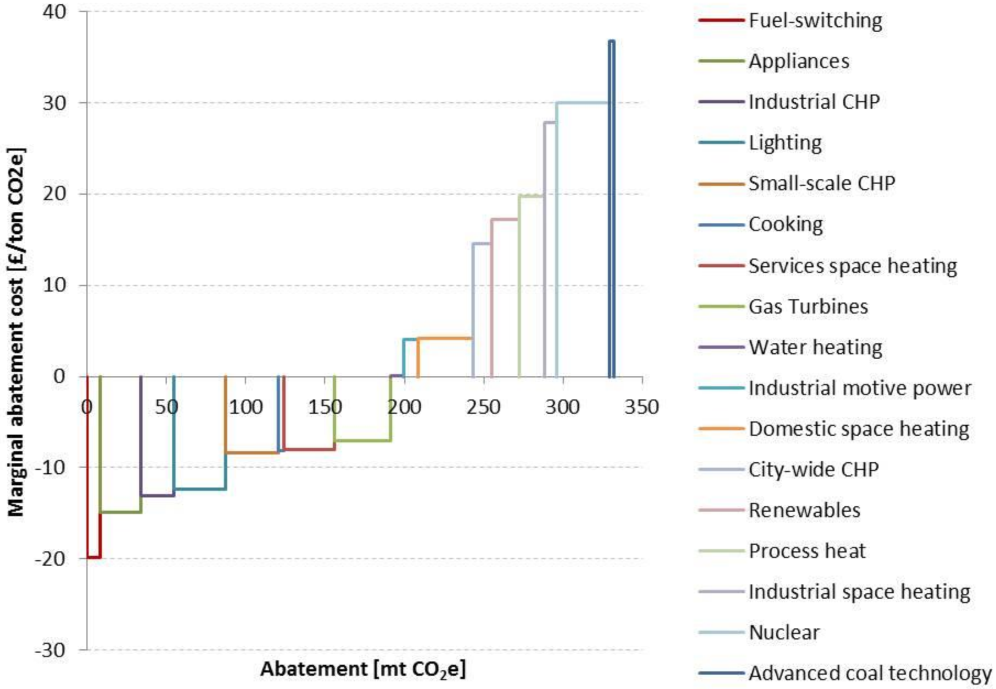
The CSC model has since been adapted to the climate change discourse as MACC. In 1991, Jackson (Jackson, 1991) presented four MACCs that allowed least cost greenhouse planning for the UK, therefore, according to Jackson, transferring the CSC model to the climate change abatement context. In practice this is done by substituting cost per kWh with cost per CO_2 abatement. Within the climate change abatement context MACC is regarded as a powerful tool. Much of the public interest in the model applied in the climate change context is accredited to the consultancy firm McKinsey & Company, who based numerous reports on the curves (Kesicki and Stranchan, 2011).

2.1 Model application

The model is, as discussed in the introduction, widespread and used by many different actors and to meet different analytical requirements. Roughly, these different purposes are possible to group into:

- **P1,** optimizing actions and investments for reaching a goal; and
- **P2,** analyzing possible market responses to price signals.

Therefore, besides the information given by PE, CSC/MACC provides additional insights to the contribution and role of individual actions contributing to the supply of the desired good. Figure 2 is a reproduction of one of the original MACCs from data within Jackson's article.



table

Figure 2. Reproduction of one of the four original MACCs for UK by Tim Jackson (Jackson, 1991).

A CSC/MACC should enable the analysis of both P1 and P2. For the P1 application, the merit of option implementation is established from left to right in the CSC/MACC. Looking at Figure 2, the idea is (assuming the ranking problem does not exist for the moment) that the option listed furthest to the left is the most economic efficient, the option second from the left is the second most efficient, and so on. Thus, from Jackson's curve, "fuel switching" is more efficient than addressing "appliances", which in turn is more efficient than addressing "industrial CHP", and so forth. To supply reductions of 120 mt CO_2e, to provide one example from the figure, "fuel-switching", "appliances", "industrial CHP", "lighting", and "small-scale CHP" need to be addressed. Furthermore, it might be noted that 191 mt CO_2e is possible to reduce through options with a negative MC. After addressing "gas turbines", remaining abatement options increase costs.

Applying the CSC/MACC model for P2 includes a number of different sub-purposes. Examples include the analysis of what would be economical to adopt given certain economic policy (Stankeviciute et al., 2008), and the effect of introducing an industry into a trading scheme such as EU ETS (Flachsland et al., 2011).

Taking the aforementioned Jackon's curve and a tax on CO_2 emissions of 10 £/t CO_2e, the MACC tells us that addressing industrial motive power and space heating would become economically beneficial investments to reduce emissions instead of paying the tax. Likewise, a tax of 20 £/t CO_2e would additionally result in the "city wide CHP programmes", investments in "renewable power technologies" and the use of "process heat", additionally becoming possible to adopt without increasing costs.

2.2 The problem of ranking options with negative marginal cost

Compared to the widespread use, little research has been made on the analytical properties or limitations of the model.

Stoft (1995) addressed some methodological considerations in Meier's (1982) original CSC model relating to the calculations discussed in section 2.4 of this thesis. Among the conclusions is a discussion on the combination of options creating different characteristics compared to if analyzed as discrete in a sequence. Stoft also expresses a skeptical view towards options with a negative marginal cost, and presents a brief discussion on an idea that cost savings are not directly related to conserved energy, for example reduced maintenance should not be accounted for in the CSC model.

Some research has focused more on system aspects in relation to the model. Flechter et al. (2009) discussed the problem of option interdependency, which refers to the idea that when one adopts one discrete option it affects other options. For expert-based MACCs option interdependency results in path dependent aspects of the model, where the local context has a high effect on the result (Morris, 2012). The problem of option interdependency affects the performance of discrete options (Kesicki and Eckins, 2012). Kesicki (2013a) raised the issue that an inability of including system-wide interactions was one of the main drawbacks of the model. This was addressed in Levihn et al (2014) for direct option interdependency, and for multi-energy systems and indirect effects in Levihn (2014a). The robustness of MACC relative energy prices and economic policy has also been addressed by among others Klepper and Peterson (2006), Delarue et al. (2010), Kesicki and Stranchan (2011), Kesiki (2013:b).

Another area which recently received attention was the difference in implementation time of various options. Vogt-Schilb and Hallegatte (2013) exemplified how an option could perform better in economic terms relative other options once the implementation time is accounted for.

The problem of ranking options with a negative cost that was introduced in the introduction is not new. After Jackson (1991) presented his MACCs in 1991, a debate between him and Wallis followed.

In the responding article, Wallis's (Wallis 1992a) main focus was on discrete options. The discussion thus elaborated on certain measures such as supply options versus demand side savings and a comparison of the advanced coal technology PFBC (pressurized fluidized bed combustion) versus CCGT (combined cycle gas turbine). Wallis did not elaborate more on why the metric was wrong, save for the model resulted in large values (positive or negative) for near zero MA. Jackson's response (Jackson, 1992) mainly focused on discrete options such as the discussion of PFBC (clean coal) versus CCGT (gas). In the second responding article by Wallis (1992b), the methodological problem of ranking negative cost options was identified and described, but much of the discussion still focused on which discrete abatement option was the best. In the last communication on the matter, Jackson (1993) elaborated on the ranking problem. In this last communication he states the ranking was correct in that to reach the same goal one must invest more in money saving options, thus resulting in greater economic savings.

There are some basic problems in the logics of this last communication. Jackson's (1991) calculations included the feasible technological potential as one parameter — why it is not possible to make more investments in an option than what is listed in the MACC on the x-axis. These constrains are also valid for other contexts such as energy efficiency in the iron and steel industry. For example, in Brunke and Blesl (2014) process and facility boundaries are identified to manage such constrains for MACC/CSC analysis of the potential for overall energy conservation, CO_2 abatement and conservation of electric power for the German iron and steel industry.

If there was no such constrain, it is still better to prioritize a investments in options with a greater effect on climate change abatement and a greater financial return (lower MC) such as option B described in the introduction. Investing more in such options would of course result in more financial return and more CO_2 abatement, which are both desirable goals. To give an example from Jackson's own curve, measures with regard to efficient lighting has a greater potential to reduce costs and results in more abatement than fuel switching (the difference in result between McKinsey&Company 2008 and Jackson 1991 is noted).

For about 20 years, the discussion between Wallis and Jackson seems forgotten until Taylor, in 2012, picked up the ranking problem in an article (Taylor, 2012). As a solution to the ranking problem, he suggests the adoption of Pareto optimization, as this according to Taylor would allow optimizing for the options that result in most abatement and cost reductions. However, such optimization cannot establish merit between options that are on the Pareto frontier. Taylor identifies this as problematic from what he defines as the two perspectives of the environmentalist and the investor. If two options are on the Pareto frontier and one results in greater financial return and the other in more CO_2 abatement, the investor would hold the option of greater financial return highest in merit, and the environmentalist the option that results in higher abatement higher in merit. There are also other problems associated with this solution as will be discussed later.

Recently, Ward (2014) raised concern for the ranking problem (unaware of Taylor, 2012) and stated the urgency of attending this problem given the widespread use of the model. Ward also elaborated on a solution by addressing a price to CO_2 emissions and thus solves what is more economically efficient to do. This is not a peer-reviewed research article though, and an analysis of the implications of his suggested solution is not performed. It is also unclear exactly what Ward suggests. Is it a shadow price relating to a market failure or estimations of future policy?

A price on CO_2 emissions is included in many scenarios used for and in CSC/MACC analysis through economic policy instruments (see for example Levihn 2014a, Klepper and Peterson, 2006; Delarue et al. 2010). This is a feasible approach and is part of what will be argued for in this article.

A shadow price approach would include guestimates of the cost induced on society if not reaching the abatement goal. This approach has some drawbacks though. While it might be argued for in relation to public costs it is irrelevant for private costs, and thus market responses. Taylor (2012) includes a discussion on this metric and dismisses it as “contestable and fundamentally unsuitable” in his article.

3 Pareto optimization as a solution to the ranking problem

The thought of Pareto optimization is to find market structures where no one is better off by a shift from one to another (Stiglitz, 2002). As I discussed earlier, Taylor (2012) uses it to rank the different possibilities that would form a bottom-up MACC, where the sequence of options results in the least cost and most abatement (Taylor 2012), ultimately aiming at reaching a state where the problem of ranking negative options such as the example given in the introduction is avoided.

3.1 Taking corporate behaviour into account

Pareto optimization, as proposed by Taylor (2012) for this context, works by determining which option(s) is Pareto efficient. In practice, this results in a methodology where the options that are better off in both MC and MA are selected first. This optimization would solve the problem of ranking option A-B-C as discussed in the introduction. The problem, however, is that if we add an option D, with -17 in MC and 8 in MA, it would not be possible to determine trough Pareto optimization if D is more desirable than option B with -15 in MC and 10 in MA (Table 2). The reason is that if we move from option D to B we are worse off in marginal cost, similarly a move from B to D results in reduced abatement. This state where the merit of options is not possible to establish is usually referred to as options on the Pareto frontier, and is within the Pareto context regarded as the most efficient options.

Table 2

Option D is added to the example from Table 1 to illustrate the problem of using Pareto optimization to solve the ranking problem of CSC/MACC.

Option	MC	MA	MAC (MC/MA)
A	-10	5	-2
B	-15	10	-1.5
C	-10	1	-10
D	-17	8	-2.1

Taylor (2012) discusses this as the investor or environmentalist dilemma. The investor prefers to invest in the option that results in the highest financial return (option D) and the environmentalist the option that supplies most abatement (option C).

According to Taylor (2012) and his use of Pareto optimization, both options B and D should simultaneously be highest in merit followed by A, and lastly C. It does provide an improvement over the traditional MAC, as it would provide the right solution before option D is introduced, and identifies that B and D prevail in either MC or MA, but it has two major drawbacks.

The first problem is, and it is essential for the context of corporate investments, that the investor that performs the investment, not the environmentalist. One perspective is that the investors invests because they expect a financial return (Stiglitz, 1993). Further, profit maximization/cost minimization enables future access to capital, which in turn is a key enabler for managing future investments.

The second problem is that Pareto optimization needs to identify the Pareto frontier, which means the simultaneous calculation of the marginal cost and abatement of multiple discrete abatement options. The problem of neglecting interdependencies has been raised in numerous articles (see for example Kesicki, 2013; Kesiki and Ekins, 2012; Flechter et al., 2009; Stoft, 1995). Levihn et al (2014) discussed and showed just how severe this shortcoming is, and how it potentially results in serious overestimations of the cost savings and abatement potential, as it fails to grasp abatement option interdependencies and the influence of the sequence options are invested in. As a result, Pareto optimization does not fulfill the requirements as good optimization for either of the purposes P1 or P2.

4 Robust relative economic policy

I will leave Pareto optimization for now and return to the traditional CSC/MACC model. In energy systems, using the expert-based CSC/MACC to understand the influence of price signals (purpose P2) is problematic due to the fact that the carbon productivity of different types of production varies. Simplified, when organised in energy markets such as Nordpol Spot and the European Energy Exchange, both the income from sales and the cost for fuels and other factors of production vary, which impact the merit of considered options.

Generally, those with the lowest variable cost will sell most energy and those with higher less. This result is an investment rule of thumb that high fixed costs are possible to trade for low variable costs and vice versa. The variable cost is based on a combination of different underlying costs. Some of the major costs are fuel, operation, maintenance, and economic policy such as subsidies, taxes and in the case of Europe, EU ETS.

As a result, the energy system merit order (ESMO)[1] varies depending on the different types of production technologies and fuels in the production mix. In practice, a result of ESMO is that one production plant with a certain technology and fuel is preferable over another during certain operational conditions, but not under other such.

4.1 The influence of ESMO

In the MACC literature, it has sometimes been argued that economic policy should be left outside the calculations (Kesicki and Stranchan, 2011). The effect of ESMO due to the different compilation of prices among different abatement options is not advisable though.

Within the climate change abatement context in relation to economic policy, the problem of applying the MACC for P2 becomes highly visible. As different production has different CO_2 intensity, an increased price on CO_2 emissions would affect the variable cost of production differently. As a result, a shift in ESMO might take place where one production technology sells more or less energy than before. If possible abatement options are related to production with different CO_2 intensity, the robustness of the MACC to the changed price on CO_2 emissions is reduced (Levihn, 2014b). Especially

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[1] To reduce the risk of confusion with the order of merit in the MACC context, ESMO is used to describe the merit order between different production technologies and fuels in an energy system.

as the ratio of fixed and variable cost also varies between different abatement options. For the CSC model, Stoft (1995) discussed that calculations were by definition often dependent on energy prices.

Delarue et al. (2010) addressed the robustness issue of MACCs in relation to fuel switching in the European power sector. They suggested that a topography chart should be used in favour of the un-robust MACCs for understanding the effect of fuel switching on CO_2 emissions in relation to the ESMO, due to the potentially different levels of economic policy.

The resulting problem for a MACC and its application in relation to purpose P2 is that at best the curve provides clues to how sensitive different options are to price policy; however, as the ranking of options is not necessarily robust to the economic policy, they are not suitable for analyzing market response to such policy. At most they are robust for such small changes that do not affect the relative variable cost between different options. As a result, a new MACC would be required for each level of economic policy one seeks to understand the corresponding market reaction of (Levihn, 2014). By including economic policy instruments in the optimization calculations, all options with a negative cost would be profitable investments for market actors given that particular economic scenario.

The total cost of new investments is also a combination of fixed and variable costs. What is profitable and how the investments will interact with the present is a combination of the ratio between these two factors (Levihn, 2014a; Levihn et al, 2014). Likewise, as the carbon intensity of different production varies among present production, it also does among different abatement technologies. As a result, the place in the ESMO and thus the number of hours in production would vary with economic policy. It affects both the financial performance and amount of CO_2 emitted or reduced.

For example, when building biomass CHP plants, the effect on factors such as CO_2, SO_x and NO_x emissions, primary energy consumption and cost depends on what other production will be substituted by the new plant (Levihn and Nuur, 2014). This in turn depends on the relative cost of all existing production units within a system.

Although the topography chart developed in Delarue et al. (2010) partly satisfies the requirements of P2 in relation to fuel switching, it does not satisfy the requirements of P1. The approach shows the amount of CO_2 emissions abatement in relation to a certain price on CO_2 emissions, but does not reveal the cost for affected market actors or why it is unsuitable to use for least cost integrated investment planning.

It should also be noted that the problem of robustness of expert-based CSCs/MACCs is relevant outside the context of options with negative MC. The issues of robustness in relation to ESMO and different price signals are also valid for options with a positive MC. Therefore, the use of MACCs such as those proposed by Jackson (1991) is not advisable for analyzing market reactions or optimizing actions in the first place, even if the ranking problem did not exist.

5 An approach to solve the problem of ranking negative cost options

A solution to the ranking problem thus requires the essential capabilities of:

1. Allow for ranking of actions (P1)
2. Allow for analysis of market reactions (P2)
3. Manage option interdependency and the ESMO effect

A solution to the problem is not far away from the original CSC/MACC model and neither is it complex. If assumed that the prime goal is financial return or cost minimisation and this is paired with fulfilling other goals, a multi-dimensional problem is created with cost as one dimension and the other goals as the additional dimensions. This also pairs with market response, as CO_2 abatement is only one concern among others (Levihn and Nuur, 2014). In the case of climate change abatement through reduction of CO_2 emissions this is possible to simplify to the two-dimensional problem of costs and CO_2 emissions. Overshooting CO_2 emissions abatement targets is not a negative concern either. The objective is in this context of how to reach sufficient CO_2 abatement while costs are minimized.

The suggestion is to simply rank the options by using least cost as the metric. This bears resemblances to what Wallis (Wallis, 1992b) suggests as a better ranking in his critique of Jackson's (Jackson, 1991) MACCs. This is also how Hamamoto (2013) created the MACC in his article, although seemingly unaware of its resulting benefits. Moran et al. (2011) also apply this ranking and show traces of being aware of the problem but do not discuss it explicitly. It is also discussed as one option suggested by Ward (2014).

Optimizing the financial return by lowering costs as much a possible puts the firm in a better position for future investments Stiglitz (1993). If there is a need for a merit between options, for example if it is not possible to manage or raise funds for all options, selecting the lowest cost options first puts the firm in a better position to manage the next. Assuming positive discount rates, this also means that the firms would be in better financial position when the possibilities to invest in abatement options with a negative MC are exhausted.

For most firms (and nations) climate change abatement is not the primary concern or core business. Rather, it is only one concern among many others.

5.1 The need for a scenario approach

Before we turn the discussion towards how the proposed analysis may be conducted, another issue must be addressed: the traditional approach (similar to Jackson, 1991), where a bottom-up MACC is drawn and used for analyzing the effect of different economic policy instruments, is problematic due to the ESMO effect previously discussed.

5.2 Managing ESMO in CSC/MACC

The model provides snapshot for a certain scenario. Both economic factors and interdependencies between adopted options affect the result (Levihn et al, 2014). This is problematic if the model is used wrongly but also provides possibilities. Levihn (2014b) performed a sensitivity analysis for the calculations used in Levihn et al (2014). This clearly showed that due to the ESMO, robustness only existed for a certain narrow band of economic policy. Furthermore, the analyzed options showed clear differences in how robust their cost and abatement performance was relative a price on CO_2 emissions.

A result of this scenario dependency is that a single application of the curve is to be avoided for understanding the impact of economic policy. A positive though is that the model is suitable for a scenario approach. The information given by the model reveals information in relation to applied goals and costs for the particular analyzed scenario (Levihn, 2014a).

Thus, using climate change abatement as an example, performing calculations for a range of scenarios is possible and allows analysis of the impact of economic policy. Similarly, electricity price scenarios could be attributed to conserved energy within the CSC model. This is in part what is suggested by Ward (2014). It also solves the robustness problem in relation to energy prices discussed by Keski and Stranchan (2011).

5.3 A comment on scenarios and Pareto optimization

Given the discussion above it is worthwhile to provide a note on whether a scenario approach solves the issues for Pareto optimization in relation to option interdependency and ESMO.

The answer lies in the fundamental strength and in this case weakness of Pareto optimization. As soon as two discrete options are on a Pareto frontier, following the conclusions from Levihn et al (2014), each of these does not only potentially affect one another; they potentially affect both earlier and later considered options. As it is not possible to distinguish between options at the frontier, it is not possible to consider if one option results in the redundancy of another, to name one example. Therefore, adopting a scenario approach to manage the ESMO effect and interdependency between considered options does not solve the fundamental issue of how to mange options on a Pareto frontier.

5.4 Application to support P1 and P2

5.4.1 Application for least cost planning

When based on a scenario, the CSC/MACC reveals how to optimise between actions and what these actions correspond to economically in relation to reaching goals. By combining two or more scenarios with two different levels of economic policy, the analysis reveals what options are economical under each scenario. It also reveals information of discrete option performance, and if the scenarios are selected carefully allows for conclusions with regard to discrete option robustness for a range of anticipated changes.

All options with a negative marginal cost would correspond to those options that under the analyzed scenario, including economic policy instruments, result in a positive reduced costs (negative MC). These options would also constitute the economically rational investment behaviour. The expected achievement towards reaching a goal, and corresponding costs, is thus possible to extract along a merit between discrete options.

This satisfies requirements for purpose P1. Climate change abatement targets would be reached through increased competitive advantage and firms would be in a better financial position to manage future investments. As was shown in Levihn et al (2014), this should include options likely to be adopted that have marginal or even negative effects on climate change abatement, if such options have a large enough positive effect on the properties of other abatement options.

To satisfy the requirements of P2, a new MACC would need to be constructed for each price level of economic policy one needs to understand. In the same manner, the robustness of discrete abatement options is revealed by analyzing a range of future scenarios. This is the only possibility to reveal rational market response to economic policy through present expert-based CSC/MACC approaches, including the one presented in this thesis.

5.4.2 Other goals and limited analytical capabilities

If firms pursue other goals than profit maximization, using least cost planning as a pure metric is of less value. Levihn et al (2014) showed that not only is it possible to introduce discrete options into the analysis even though they are based on other criteria, it is also a necessity if we have strong option interdependencies. If the selection of all discrete options is based on other criteria than marginal cost minimisation, the curve adopted through an iterative systems approach would still reveal how option interdependency affects a two-dimensional problem, for example the effect on a firms marginal cost and CO_2 emissions.

For the normative metric of least marginal cost I suggest in this thesis the curves would, for example, provide insights to whether goals on CO_2 emissions abatement goals are satisfied by selected options or not. This optimization would be bounded by the analytical and computational capabilities we possess. This is not limited to the discrete options but also in relation to the scenarios used.

5.4.3 Implications for the definition of economic efficiency

The discussion on the metric problem of cost per unit has mainly been in the context of marginal abatement cost curves. Still, the curve of the CSC/MACC model is not what constitutes the ranking problem. The problem is present with or without these curves.

All optimization of economic efficiency defined as least cost per unit is problematic when costs could take negative values. Something with potential implications for many other models. For situations when costs take negative values, minimizing cost per unit, simply does not result in desired outcomes. For an investor, rather the goal should be maximizing profit / minimizing costs for the given or required supply. Thus least cost should be the metric with a boundary conditions of required supply, whether its water usage, waste management, improving air quality or meeting CO_2 abatement targets.

6 Conclusion

Optimizing for least cost per unit is problematic when costs could take negative values. Unfortunately, least cost per unit supplied is a common definition used in the context of assessing economic efficiency. One tool using this definition is MACC. MACCs are widespread and potentially useful tools for optimizing sequences of investments, or assessing the impact of policy.

The identification of the ranking problem for the partial equilibrium inspired least cost planning model called CSC or MACC is not new. In Wallis (1992a), Wallis (1992), Taylor (2012), and Ward (2014) the problem was discussed in detail. A further claim of the urgency to solve the problem was expressed in the October 2014 by Ward (2014). Of these, Taylor (2012) proposed a solution in Pareto optimizing the options with a negative MC.

In this article I discussed that adopting Pareto optimization to solve the problem would result in undesirable effects. Moreover, this optimization is not advisable when there exists interdependencies between discrete abatement options.

These dynamics between options has a further consequence. Expert-based/bottom-up CSCs and MACCs evaluating and analyzing specific technologies and actions are not robust to exogenous factors such as economic policy or energy prices. This is simply because it is not possible to determine energy balance without taking such instruments into account. These option interdependency problems have been highlighted by amongst others Delarue et al. (2010), Kesicki and Stranchan (2011), and Levihn (2014). Potentially, they affect both the ability to reach the desired goal and the cost associated with each action. As a result, it is not advisable to use a single MACC for understanding the market effect of economic policy, for example.

What it boils down to is a need to adopt a scenario approach combined with a systems approach. This is not easy as both of the two dimensions analyzed with the CSC/MACC model could have both private and public properties. It should also be noted that there is a need to sometimes account for implementation time of different actions (Vogt-Shilb and Halegatte, 2014).

A solution that fulfills the purpose of using MACCs for options with a negative marginal cost is not far away though. Using least cost as a metric would fulfill the requirements of least cost integrated planning when options result in a negative marginal cost. It should be noted though that if least cost is not the goal another metric would be needed, but would not per-se result in least cost planning. Following the original iterative methodology by Meier (1982), with the adoptions suggested by Levihn (2014), this allows for handling abatement option interdependencies.

Furthermore, to manage dynamics between options and the system of which they are part of, expert-based or bottom-up CSCs and MACCs should always be based on a scenario approach. By comparing curves relating to different scenarios it is possible to both optimise actions, policy and understand the effect on cost and associated goals such as CO_2 abatement.

Most importantly, though, optimizing for least cost per unit is never advisable if costs could take negative values.

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