KTH Industrial Engineering and Management

Investments, system dynamics, energy management, and policy:
a solution to the metric problem of bottom-up supply curves

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Abstract, English

Today, issues such as climate change and increased competition for scarce resources puts pressure on society and firms to transform. Change is not easily managed though, especially not when relating to production or consumption of energy carriers such as district heating or electric power. These systems do not only have strong dynamics internally, but dynamics between multiple technological systems must sometimes be considered to effectively manage response and strategies in relation to change.

During the early 1980s, an optimisation model founded on an expert-based approach was developed based on the partial equilibrium model to enable the evaluation of different actions to reach a target. This model — often referred to as marginal abatement cost curve (MACC) or conservation supply curve (CSC) — is used by academia, industry and policymakers globally. The model is applied for causes such as energy conservation and waste management, but also within the climate change context for optimising CO_2 reductions and governmental policy. In this context, the model is used by actors such as the Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA) and World Bank, and by the consultancy firm McKinsey & Company, who use it extensively in different analysis.

This model has many drawbacks in relation to managing interdependencies between different options, but more specifically the metric used for ranking options with a negative marginal cost has a design flaw leading to biased results. As a solution Pareto optimisation has been suggested, but is problematic given the dynamics within and between energy systems.

The purpose of this compilation dissertation is to improve the ability for industry and policymakers to effectively manage change and reach set targets. In particular it develops our knowledge of how to account for option interdependency within and between technological systems. Furthermore, the ranking problem relating to expert-based least cost integrated planning is addressed.

This dissertation also provides policy and managerial implications relating to the issues of energy conservation, CO_2 abatement, and SO_x and NO_x reduction in relation to the district heating system in Stockholm. Implications are also provided for the interaction with other systems such as the Nordic electric power system.

Sammanfattning, Svenska

Klimatfrågan och konkurrens om knappa resurser medför ett förändringstryck på nationer och företag. Att hantera förändringar har aldrig varit enkelt, vilket är tydligt bland företag inom energisektorn såsom el och fjärrvärmeproducenter. Energisystemen dessa företag är del av har stark intern dynamik, men även dynamik mellan olika energisystem är vanligt. Detta måste tas i beaktande när strategier och planer för att hantera förändring utformas.

Under början av 1980-talet skapades en optimeringsmodell baserad på den nationalekonomiska jämviktsmodellen för att kunna utvärdera olika specifika möjligheter att nå ett mål, t.ex. energibesparingar. Denna modell, som idag ofta benämns MACC (Marginal Abatement Cost Curves) eller CSC (Conservation Supply Curves), används idag av akademin, industrin och myndigheter inom områden så som energibesparingar, minskade CO_2-utsläpp, sophantering och design av ekonomiska policyinstrument. De icke-akademiska användarna inkluderar FNs klimatorgan IPCC, IEA och Världsbanken. Även konsultfirman McKinsey&Company använder modellen regelbundet i olika studier.

Tyvärr har modellen många begräsningar när det kommer till att hantera dynamiker mellan de specifika åtgärder som identifierats för att nå ett mål. Den allvarligast begränsningen utgörs dock av ett optimeringsfel som leder till felaktiga slutsatser om prioriteringen mellan de åtgärder som har en negativ marginalkostnad. Som en lösning på detta problem har pareto-optimering föreslagits, vilket denna avhandling dock visar är problematiskt på grund av de dynamiker som finns inom och mellan energisystem.

Det övergripande syftet med denna avhandling är att förbättra möjligheten att hantera förändringar och nå uppsatta mål. Specifikt diskuteras hur beroenden mellan olika åtgärder för att nå det satta målet kan hanteras. Avhandlingen adresser även problemet att prioritera mellan åtgärder med negativ marginalkostnad.

Utöver detta bidrar avhandlingen med praktiska implikationer för politiker, myndigheter och företag involverade i fjärrvärmeproduktion i Stockholm. Slutsatser dras kring energibesparingar och minskade utsläpp av CO_2, SO_x och NO_x. Praktiska implikationer ges även för hur system som detta fjärrvärmesystem samverkar och interagerar med det nordiska elsystemet.

Foreword

Finishing a PhD dissertation is in no sense straightforward, neither is the format given. Dissertations in the form of a compilation of papers take many shapes, one of which is merely a summary of what has been done. A second form is a more integrated analysis of how the papers contribute to a common goal. The third is where the appended papers are used to further theorise and thus make the thesis contribute further than merely relating a story of what has been conducted during the process that shaped it. The last approach potentially contributes more to knowledge, as it does not focus on descriptions and summarisation like traditional introductory texts, but rather on presenting new ideas and writing not found elsewhere in the papers (Frishammar, 2001).[1]

This thesis is based on the last format outlined above. The primary reason is that early in the process, a fault in a model widely used by academia, policymakers and corporations was identified. But to mend it tools needed to be developed first, tools that took the shape of the papers included in this compilation dissertation. Just as with a wrench and a screwdriver, the papers have their individual functions and contribute to solve problems on their own. However, they might also be combined, just like the wrench and screwdriver are used for bolted joints, to solve a more complex problem than what they solve individually.

I have many thank yous for the people who have supported this journey. I will probably forget someone, so apologies for that!

I would also like to thank my supervisor Cali Nuur for the support during this process. Staffan Laestadius has never formally been listed as my supervisor, but he has in many ways functioned as one. I would also like to thank my co-supervisor Henrik Blomgren for convincing me to start the PhD journey. And thank you to Hossein Saharokni for the cooperation and many good discussions.

I would also like to thank my fellow PhD students and all scientific cafés. Stefan, Charlotta, Maria, and Caroline — this has been much fun!

I would like to thank Fortum Värme for the teamwork and for enabling this project, and in particular Anna Vidlund, Ove Åsman and Erik Dotzauer have been essential in the process of collecting, analyzing and discussing the data that provided the foundation for this thesis.

Then there are different opponents and members of the grading committee. Stefan Fölster and Pelle Lundqvist were opponents for my thesis proposal. Rurik Holmberg performed an opposition on my half-time seminar and Erik Dahlquist was the opponent on my final seminar; thank you. I would also like to thank Hans Lööv for performing the quality audit on this dissertation.

I would like to thank my soulmate — my fiancée Ulrika. I know the last half year has not always been easy; thanks for all your encouragement, warmth and support!

The final thank you goes to the Swedish Energy Agency provided the funding for this project through the project 'Investments in energy efficiency and climate change abatement: revising marginal cost curves as an optimization model'

[1] Also, it is more fun.

List of appended papers

[Paper I] Levihn, F., Nuur, C., Laestadius, S., 2014. ”Marginal abatement cost curves and abatement strategies: taking option interdependency and investments unrelated to climate change into account”. *Energy*, vol. 76, pp. 336-344

[Paper II] Levihn, F., Nuur, C., 2014. “Biomass and waste incineration CHP: the co-benefits of primary energy savings, reduced emissions and costs”. *WIT – Transactions on Ecology and the Environment,* vol. 190, pp. 127-138

[Paper III] Levihn, F., 2014. “CO_2 emissions accounting: Whether, how, and when different allocation methods should be used”. *Energy*, vol. 68, pp. 811-818.

[Paper IV] Sharokni, H., Levihn, F., Brandt, N., 2014. ”Big meter data analysis of the energy efficiency potential in Stockholm's building stock”. *Energy and Buildings*, vol. 78, pp. 153-164.

[Paper V] Levihn, F., Nuur, C., Blomgren H., 2011. ”Corporate response to climate change mitigation: What can we learn from annual reports of European industries?”. *International Journal of Industrial Engineering and Management*, vol. 2, pp. 77-86.

1 Introduction

1.1 Background

Organising 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).

There was and is a strong relationship between economic growth and the consumption of energy (IEA, 2009). Fuels and energy carriers such as electric power are consumed to enable us to travel, heat our homes, cook our food, but also produce and transport the goods and services we consume (Cullen and Allwood, 2010). Thus, as more nations develop and the world economies grow, so too does the demand and competition for scarce energy resources (IEA, 2013). Globally, the lion part of the energy used is different fossil fuels contributing to increased levels of greenhouse gases in our atmosphere (IPCC, 2014; IPCC, 2007). The supply of energy is thus central for climate change, and a need to reduce anthropogenic CO_2 emissions during the last decade has also provided what Erik Dahmen a half century ago termed as a transformative pressure on many industries (Dahmen, 1950).

Many nations and industries aim to secure access to energy by reducing the dependency on certain fuels and/or technologies (Shin et al., 2013). These issues are not only a concern for energy utilities and policymakers, as they exist in many different industries and affect productivity and competitiveness. For the energy intensive industries, such as the iron and steel industries, energy costs represent a large share of gross added value. Therefore, energy efficiency and conservation that increase productivity can be a decisive factor of competitiveness (Brunke and Blesl, 2014).

Adapting new or different technologies, fuels or processes is not easy. Change is a process that could result in creative destruction, where recourses are taken from the existing to enable the new (Schumpeter, 1942). Yet, firms often face lock-in around their present technologies and processes, which prohibits a firm to change (Dosi, 1982). Resources are allocated elsewhere, resulting in a need to obtain sufficient new capital if new alternatives are to be explored (Nelson and Winter, 1982). This is especially true for some of the more capital intensive industries, where the technological lifespan of investments is sometimes more than 40 years. Large scale production of energy carriers such as district heating and/or electricity completed this year could possibly be expected to be used by 2050. For nuclear power the technical lifespan could be even longer, and plants completed this year could be in use beyond 2070. So much change during this timespan adds to the complexity of decisions related to the use of energy. Ultimately, strategies adopted today will affect many future generations (Wijermars, 2012).

These strategies also affect what other strategies might be adopted due to the dynamics within and between different energy systems. These dynamics include circular causality and strong interactions between different options (Jeon et al., 2015). The outcome of an action is thus determined by its own effect on the system and its parts (Forrester, 1971). Likewise, a change to an energy system might affect many other systems of which it is interconnected. Constructing a new waste incineration combined heat and power plant is a good example of this. The effect of such action does not limit itself to the district heating system it will be part of, but interacts with the electricity network, waste management, the greenhouse effect (in either way or the other), and so on.

1.1.1 Private and public domains

Almost a century ago, Pigue (1920) discussed the problematic situation wherein a difference in motives of the public and private domain exists. A result of such differences is that firms and consumers do not produce and consume at an optimal level for society. Emission of anthropogenic greenhouse gases, such as CO_2, is one such issue. The cost for managing eventual climate change is not reflected in the price of using the energy resources contributing to larger consumption than what is desired (IPCC, 2014).

Energy sectors worldwide are transforming to meet demands of energy security and reduced dependency on certain energy sources. The processes of globalisation, population growth and industrialisation have combined to increase worldwide demand for fossil fuels. Some of the largest firms on the globe are involved in the extraction and distribution of fossil fuels. At the same time, the threat of climate change and measures to mitigate it have resulted in several policy instruments to reduce the difference between public and private goals, which thereof influences the long-term strategies of industries. Not only actual policy, but expectation or uncertainty thereof affects what strategies firms adopt (Fischer, 2007).

As the world economies grows so does the competition for earth's resources. Several nations have put energy security on the top of their agenda for future development, recognising that the supply of energy is a necessity for increasing or preserving current standards of living and welfare. For instance, we have recently seen an expansion of shale gas extraction in North America (Krupa and Jones, 2013). This would reduce US dependency on the traditional oil producers in the Middle East. When Sweden in the middle of the last century pursued nuclear power, it was reducing its dependency on importing energy. Today, the question of a Swedish energy system with or without nuclear power is high on the political agenda.

The exploration of new fossil fuels impacts energy prices. The shale oil and gas extractions in North America have resulted in reduced market prices of coal in Europe (IEA, 2013). When price reduces its demands increase. It has been recognised, however, that conserving energy is key in relation to climate change, energy security and increased competitiveness (IEA, 2009).

Different industries are affected differently by changing market conditions. Take the example of mitigating climate change and CO_2 abatement (avoiding or reducing CO_2 emissions). The financial risk related to climate change is asymmetrically distributed between and within different industrial sectors (Busch and Hoffman, 2007). These differences depend on the dependency on carbon-based fuels, and certain processes and technologies.

Unfortunately, for industries, the above-mentioned examples are just scratching the surface of what is occurring. Present actors have historically defended themselves against new threats (Utterback, 1994). Many existing technologies challenged by new technologies improve. Incentives like environmental taxes are met with industrial lobbying arguing that these would make them less competitive for production operating in regions without lower taxes (Wijermars et al., 2012).

Firms and nations are not uniform in their actions, but rather they apply different strategies to grow and/or survive. For the energy sector many paths exist to reduce CO_2 emissions and increase resource utilisation, but which technologies should be adopted? International firms also face different contexts in different regions affecting what is a successful action or not (de Wit and Meyer, 1998/2008). What gives the desired effect thus varies and firms explore different paths. Firms that are able to adopt and mange change have a greater chance of survival, including increasing their financial performance and competitiveness (Nelson and Winter, 1982). Yet, is the right path, for example, nuclear power, solar cells, natural gas, wind power, or load management? Or is it more efficient energy consumption?

1.1.2 *A model for optimising sequences of investments*

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 optimisation 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 prioritise 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" [2] 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 Sranchan, 2011).

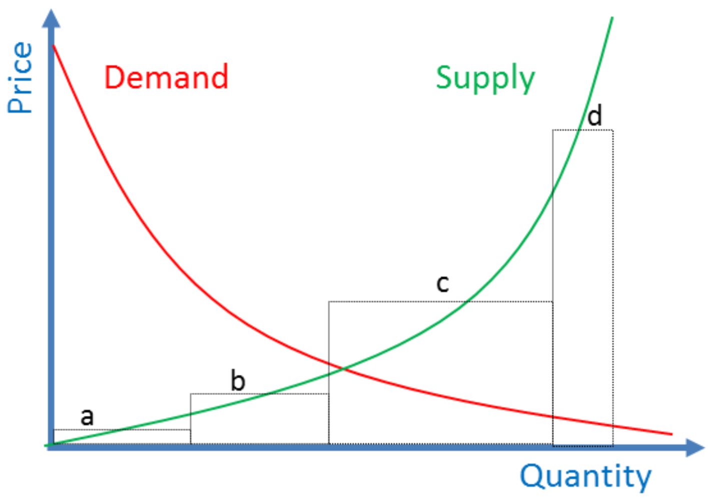

Figure 1. In CSC, the "supply curve" is estimated through analysing the effect of adopting discrete options, corresponding to the boxes **a-d**. In this example, adopting option **a** and **b** would almost meet the demand.

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 cost per unit(s) supplied. The curves are used in numerous studies for a variety of applications (discussed further in Chapter 2).

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

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[2] It should be noted that the model after adaptation does not exactly equal an economic supply demand function (Stoft, 1995).

(2014) and Wallis (1992a; 1992b), the application of this bottom-up or expert-based optimisation approach is problematic when considering actions with a negative marginal cost.

1.1.3 Illustrating the metric problem

While some find the notion of negative costs unintuitive, it is a result of the model being defined through the two dimensions of marginal cost and units supplied. Marginal defines for this model the change in state before and after adoption of an action, which could both increase and reduce both supply and the cost of supply. In some situations, and commonly within the climate change abatement application of the model, options exist that reduce the cost of supply. Although this, for example, could be noted as an equivalent to a positive net present value for adopting a supply option (Brunke and Blesl, 2014) (depending on underlying calculations), the function is still defined through marginal cost per unit and units supplied.

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 optimisation 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 prioritise 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 prioritisation sequence of B-A-C.

If we use the metric of the partial equilibrium model (as well as in present CSC/MACC), that is 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 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 supply and cost reductions, 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 analyse 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 analyse 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 analyse 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) analysed 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 in *Energy Policy* and the scientific community does not seem to have taken notice of its methodological implications.

In 2012, Taylor (2012) raised the problem again in an article on the problem in *Energy Policy*. Taylor proposed avoiding the optimisation problem by utilising Pareto optimisation instead. The thought of Pareto optimisation 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 optimisation is problematic though in relation to energy systems and does not solve the metric problem, as I will discuss later in this thesis.

Still, MACCs with the problematic optimisation continue to be published in articles in high ranked journals, as well as an increasing number of corporate reports that utilise 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.

In the IPCC's 2014 report AR5, MACC was presented as one tool to analyse 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[3]. The IPCC generated scenarios in the report are based on a third approach they label , 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.

[3] System-wide simulations where interactions between different developments are accounted for. The difference compared to regular advanced energy systems simulations is unclear.

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 in *Energy Policy* 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 optimisation problematic of the model. This is important given the widespread use of the model and its importance to the climate change abatement context.

1.2 Purpose and problem statement

The overall purpose of this dissertation is to improve firms and policymakers' ability to manage change and effectively reach a desired target. It contributes to our knowledge on how to take interdependencies and dynamics within and between multiple technological systems into account while performing investments and managing energy-related issues. In addition to the individual contributions of the appended papers and compiling them in this thesis, this cover essay additionally contributes by:

> *addressing problems relating to expert-based least cost integrated planning through partial equilibrium-based approaches, when options have a negative marginal cost.*

The following arguments are established:

- Pareto optimisation does not provide a good solution for the optimisation problem.
- Expert-based CSCs/MACCs relating to energy systems are not a robust relative economic policy.
- Adopting actions with the lowest marginal cost first provides a valid metric that solves the ranking problem.
- A scenario approach is needed for CSC/MACC analysis, independent of which metric is used.

This is a lot easier given the important groundbreaking work already conducted by Wallis (1992a; 1992b), Taylor (2012) and Ward (2014) in identifying and providing proof for the existence of the problem. Researchers within the field generally seem unaware of the article by Moran et al. (2011), but it is also important as it provides an example that together with Hamamoto (2013) is close to the solution I will propose, motivate and elaborate on in this thesis.

1.3 Short introduction to appended papers

As I have previously discussed, CSC/MACC is a two-dimensional problem wherein the cost of reaching a goal is optimised. Thus, both the cost and goal constitute two dimensions that define the problem. For the climate change issue and MACC the dimension relating to reaching the goal is most often the abatement of greenhouse gas emissions. Planning and execution of the individual articles appended in this thesis has mainly focused on solving problems relating to either of the two dimensions and how they are integrated, as well as methods and applications relating to the model.

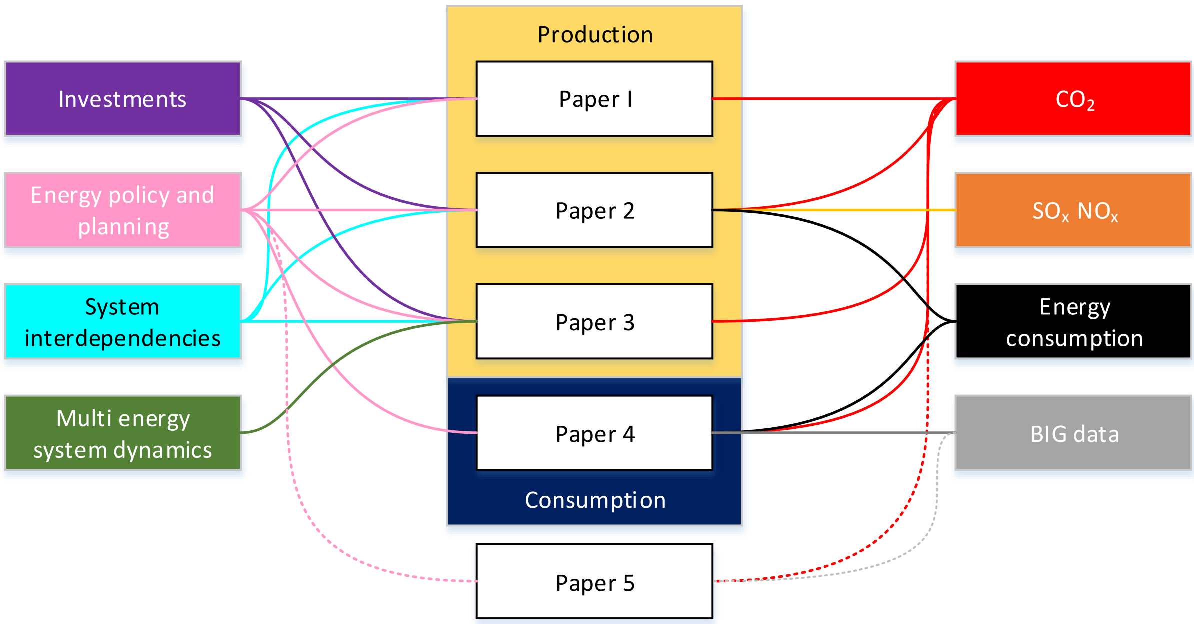

Figure 2. Issues addressed by each individual paper appended in this thesis.

The appended papers and what they relate to is listed in Figure 2. Before presenting the articles and related conclusions in more detail in Chapter 4, I will provide a brief overview of them.

1.3.1 **Paper I** — *Marginal abatement cost curves and abatement strategies: taking option interdependency and investments unrelated to climate change into account*

The first paper focuses on the integration of MACC, and the problem of when the different options that are part of a MACC are interdependent. This is often the case when considering abatement options relating to the production of different energy carriers, but is also evident in other contexts. The article has implications for investment optimisation, energy policy and climate change abatement. It discuss intersystem interdependencies between different investment options related to the district heating systems in Stockholm. The article was published in vol. 76 of *Energy*.

1.3.2 **Paper II** — *Biomass and waste incineration CHP: the co-benefits of primary energy savings, reduced emissions and costs*

The second paper delves into two of the abatement options discussed in Paper I. The article was published in volume 190 of the *WIT Transactions on Ecology and the Environment*. It contributes by diving deeper into the interdependencies between different possible transformations of an energy system, but also investigates how other factors, namely SO_x and NO_x emissions, and primary energy consumption relate to CO_2 abatement. The article provides insights on relationships between different technologies and fuels applied in production, and is relevant to investments and energy policy alike.

1.3.3 **Paper III** — *CO_2 emissions accounting: whether, how and when different allocation methods should be used*

Along with the work developing different analysis relating to CO_2 abatement, I stumbled over the highly infected debate on emissions allocation. This resulted in the third article published in volume 68 of *Energy*, which happened to be the first of these three integrated articles to be published. It focuses on the problems of accounting and allocating CO_2 emissions when taking part in both a larger multi-energy system and an emission allowance system such as the EU ETS.

This is highly important in understanding different goals and types of MACCs and CSCs. Thus, the article discusses wider system interdependencies between different actions compared to Papers I and 2. This paper discusses different systems at different system levels.

1.3.4 **Paper IV —** *Big meter data analysis of the energy efficiency potential in Stockholm's building stock*

The fourth article explores the emerging trend of collecting and using big meter data for analysing different problems. With access to hourly metering data of buildings connected to district heating in Stockholm, 13 GB of raw data were available. While Papers I, II and III analyse production related issues, this paper instead focus on the consumption side. The article is focused on energy conservation and the energy performance of buildings. This is in the paper related to the production side and thus draws conclusions on the relation between energy conservation and CO_2 abatement. While the CSC/MACC is not explicitly discussed in the paper, it is a first explorative step in using big meter data for such analysis. The article was published in vol. 78 of the journal *Energy and Buildings* and provides implications for policymakers in relation to the potential for conserving energy among the building stock in the city of Stockholm.

1.3.5 **Paper V —** *Corporate response to climate change mitigation: What can we learn from annual reports of European industries?*

Additional to [Paper I-IV], a multitude of articles have been written during the PhD process. These include many conference contributions and different working papers. One paper, published in volume 2 of the *International Journal of Industrial Engineering and Management,* focuses on how climate change issues have developed within public European firms. This article was published early in the PhD process, and I have had different opinions on including it in the final thesis or not. In the end, it has been important to develop the other work and the context in which firms exist, and thus the context of the other included articles.

1.4 Structure of thesis

Apart from this introductory chapter this cover essay consists of seven additional chapters.

Chapter 2 presents some of the literature on investments and least cost integrated planning, and provides an overview of some basic concepts and theories used in this thesis. In Chapter 3, an oversight over the methodological approaches used in the studies is presented. After this, the appended papers are summarised in Chapter 4. In Chapter 5, a discussion and analysis is conducted to establish the set of arguments this thesis seeks to address. The thesis is concluded in Chapter 6. Chapter 7 provides implications for management and policymakers. Chapter 8 discusses the limitations of the work conducted with areas that need attention in future research.

Personally, I have never been a fan of footnotes. However, as this thesis aims at larger audience than scholars researching the CSC/MACC model, I have included some footnotes for the reader previously uninitiated to the topic of this dissertation.

2 Investment optimisation and modelling

This chapter presents some of the literature on investments and least cost integrated planning, and provides an overview of some basic concepts and theories.

2.1 Investment optimisation

2.1.1 General introduction

One goal of a firm is financial return in order to make it attractive for investments, something that is essential for the ability to raise enough capital to manage change and sustain competiveness. This might seem obvious to some, but it is nonetheless important to point out for the remaining discussions in the thesis.

According Joseph E. Stiglitz (1993), firms face three possibilities for how to manage earnings: capital gain, dividend or kept in the firm to enable future capital gain and dividend. According to Stiglitz, "an investment is the purchase of an asset in the expectation of receiving a return" (Stiglitz, 1993, pp. 252). Change therefore secures future earnings, a transition that necessitates access to capital. A consequence is that the ability for a firm to manage future investments is based on previous earnings. When choosing between investments, prioritising those investments that result in the highest gains puts the firm in a better position to manage future investments.

There is a close link between a firm's financial performance and attractiveness for investors (Sueyoshi and Goto, 2011). The access to capital is crucial for the ability to invest in many of the climate change abatement options. For electric power producers, for example, financing investments is one of the most crucial concerns (Kohdorovsky et al., 2014; Gitelman, 2014).

There is also the neo-classical economic view on investments as expressed by Keynes (1935), where emphases is put on investments resulting in a series of prospective gains. The main goal is the economic return after the production costs are deducted from the value of the output through the life of the asset. Thus, not only is the initial investment cost of concern, but also the stream of income and costs resulting from the investment.

2.1.2 Constrains on conservation or abatement potential

There is a limit to how much abatement or conservation measures a firm can invest in. Take the utility used in Papers I, II, III, and IV as an example: the utility operates in a system where the demand for district heating depends mainly on outside temperature. There is about 12 TWh of heat demanded each year but with daily and seasonal variation, thus creating a limit for energy production and the conservation potential. Furthermore, in the present generation mix, there is only certain production that emits anthropogenic greenhouse gases, and this provides an upper limit for how much abatement is possible to perform in this particular system. These two factors also work together and create constrain for how many units of a certain option (e.g., new production plants) are possible to introduce into the system. A limit of discrete option implementation has been assumed throughout the discussions in this thesis.

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.

2.1.3 Constrains resulting in negative cost options

According to economic theory, efficient markets should distribute resources in the most efficient manner possible. This is often referred to as the efficient market hypothesis. Advocates of this perspective doubt the existence of possible actions with a negative marginal cost in itself (Taylor, 2012).

There is a classical joke illustrating the hypothesis and its drawbacks. It goes something like this:

> *The young economist looks down and sees a $20 bill on the street and says, "Hey, look a* $20 *bill!" Without even looking, his older and wiser colleague replies, "Nonsense. If there had been a* $20 *bill lying on the street, someone would have already picked it up by now.*

The idea is that if there were opportunities for profit someone would have taken them already. There are a number of reasons why not all actions that are efficient in a strictly economic sense are not already adopted by market actors (Cagno and Trianni, 2014). This result of market inefficiencies, as an economist would put it, provides a scope for harvesting "the low hanging fruits" (Lahn and Preston, 2013). Institutional, political and social barriers, but also economic explanations, explain the existence (IPCC, 2014).

Particular constrains by which such options exist include transactions costs and access to capital, to name some examples. The influence of path dependency and lack of information has also been emphasised in research related to MACCs (Kesicki and Stranchan, 2011). Recently, it was also discussed that the actual business model of a firm in itself could constrain change (Tongur and Engwall, 2014).

All available options and the effect of investing in them cannot be known or analysed by market actors (Simon, 1955). Even a game with limited possible outcomes such as chess is too complex for every possible combination of moves to be fully analysed (Simon, 1972). The issue of implementing the options in practice must also be considered.

Large infrastructure projects are not finished overnight. Project management for constructing complex production facilities is advanced, and a firm's ability to manage parallel projects is limited. The utility discussed in Papers I, II, III, and IV has about 700 employees, at different functions and a turnover of slightly under €1 billion. As I write this,[4] an additional 800 contractors are simultaneously working on the construction of a new 450 MW plant called KVV8.[5] Managing this project locks a lot of the available resources the firm possesses, both financially and in terms of human capital.

Returning to the joke of the $20 bill on the sidewalk and connecting it to the example of the utility above, it also takes time and resources to identify and pick the bill up. In the case of constructing KVV8, the actual time for picking the bill up seems to end at eight years after the decision to do so.

2.2 The prevailing model

2.2.1 Model history

Organisations 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 optimisation model of CSC was developed at the Lawrence Berkley National Laboratory, which resulted in a PhD dissertation by Meier in 1982, and an article by Meier, Rosenfeld and Wright in *Energy* the same year.[6] Inspired by the partial equilibrium model of supply and demand, the idea was to estimate which energy conserving actions were economically favourable and how much electricity would be made available by investing in them. The goal was to determine which options had the lowest cost per

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[4] Late August 2014.

[5] Presently, the largest plant of its kind in the world.

[6] A conversation with Rosenfeld about the models origin is presented in Stoft (1995).

additional kWh. In other words, which investments were most economically efficient with the aim of creating the "supply curve"[7] for making extra kWh of electricity available to the market.

In his work, Meier (1982) provided a derivation of the optimisation 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 prioritised. 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)[8] presented four MACCs in an article in *Energy Policy* that allowed least cost greenhouse planning for the UK, therefore transferring the CSC model to the climate change abatement context. In practice this is done by substituting cost per kWh with cost per 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).

2.3 Classification of the approach

As CSC/MACC originates from a partial equilibrium model it is important to be clear on the different takes on the model that exists. Unfortunately, there is lack of consensus today on how to classify these curves within the scientific domain. Fortunately, the division is mainly between two classifications.

The first classification differentiates between model- and expert-based approaches. Among articles using this classification, we find Wächter (2013), Delarue et al. (2010), and Klepper and Peterson (2006). In these, the model-based curves are further classified as either top-down or bottom-up. The other main classification differentiates between bottom-up and top-down, where the expert-based approach is classified as a type of bottom-up approach. Among the articles utilising this classification system we find Kesicki and Stranchan (2011) and Taylor (2012).

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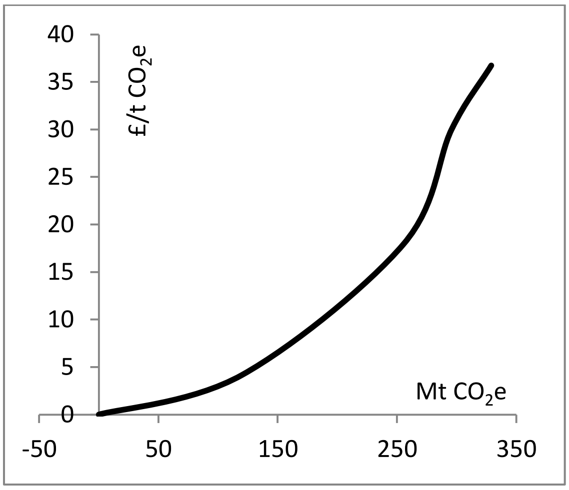
7 As stated in the introduction, it should be noted that CSC after adaptation does not equal an economic supply demand function (Stoft, 1995).

8 In this article, it is uncertain if the iterative methodology from Meier (1982) has been adopted or not.



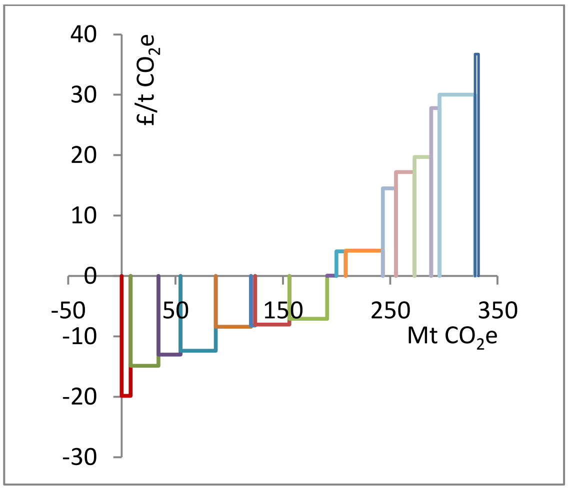


Figure 3. A comparison of smooth top-down curve (left) with the "boxed" bottom-up curve based on estimations/calculations of discrete abatement options (right).

In this thesis, the latter classification is used and the conclusions made are generalised for all bottom-up curves, where individual estimations are made for the effect of each discrete action considered. This also aligns with the general definition of approaches for analysing energy systems by Connolly et al. (2010).

2.3.1 Model-based top-down

One is the traditional application within economics, usually referred to as top-down created curves. The top-down approach is generally based on partial equilibrium models to supply a smooth supply curve (see for example Morris et al., 2012; Klepper and Peterson 2006; Crique et al., 1999). These curves are technologically neutral and do not consider discrete climate change abatement options. As such they show the amount of abatement obtained by economic climate change policy, or the cost for reaching a certain abatement target. Thus, they are useful for the analysis of appropriate tax levels to reach certain goals or to understand the effect on the allowance cost due to a certain cap within cap and trade systems such as the EU ETS.[9]

2.3.2 Bottom-up/engineered/expert-based

The other dominant variant is the bottom-up or expert-based MACCs based on an engineering approach. This approach is what was proposed by Meier in 1982, and involves an iterative optimisation approach for discrete options for finding the least cost sequence. The resulting curves differ in that instead of a smooth supply curve the curve is based on boxes corresponding to each discrete action such as those found in Figure 1. To enable such analysis, the approach necessitates a detailed analysis of possible options (Klepper and Peterson, 2006). As outlined in the introduction, engineered MACCs are commonly used in both practice and research, and according to Kesicki and Stranchan (2011) bottom-up is the most common approach for MACC studies today.

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[9] The use of top-down CSC/MACC is not covered by this thesis.

2.4 Calculations of marginal cost and supply

2.4.1 Negative costs and supply

Costs could be reduced and increased, as could supply. As a result, MACC/CSC could theoretically contain options belonging to any of the quadrants in Figure 4.

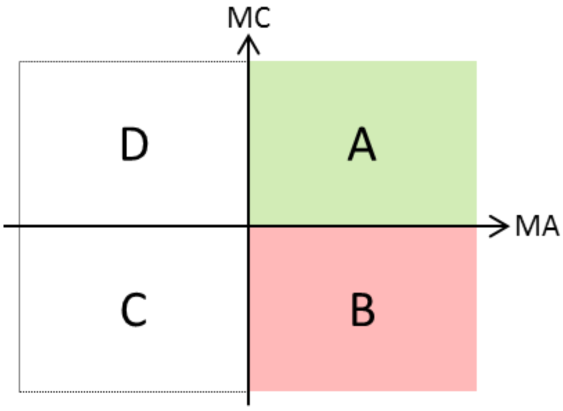

Figure 4. The space defined by the CSC/MACC model.

The PE model in economics and its smooth supply normally concerns quadrant A. Given different constraints in behaviour the other quadrants must also be considered. The definition of the CSC/MACC model through the space in Figure 4 is the reason for why negative costs are used as a concept, rather than increased profit or another concept. It is a result of how the model is defined. Thus, when discussing the model and options analysed, costs and abatement (supply) could hold negative values.

Meier (1982) only included the options belonging to quadrant A in his original work, that is options that increase the supply (MA) of kWh through increased MC. As was discussed in the introduction, using the CSC/MACC model when options belong to quadrant B is problematic.

Quadrant C and D are in general not considered in CSC/MACC analysis. However, situations exist wherein options belonging to quadrant C and D would need to be considered. For instance, if the economic and abatement performance of discrete options are affected by other options, also options not resulting in the desired supply must be considered (Stoft, 1995). For the climate change context, such options are those actions by firms that increase CO_2 emissions, while they increase profit (negative MC and MA) and affect the performance of other options. To give an example, building a new steel plant could provide such an option. Options that belong to quadrant D are also possible, for instance substituting nuclear power for natural gas power plants. This substitution would increase CO_2 emissions and could, given certain contexts, increase costs.

2.4.2 Calculation methodologies and definition of marginal cost and supply

Multiple methodologies could be considered for calculating MA and MC. The case used for the first CSC curves (Meier, 1982; Meier et al., 1982) was conserving energy amongst households in California. For many appliances and energy consuming products used in households in warm regions, the only main cost of investing in more efficient technologies is the capital cost, besides the costs of the energy that will be consumed.

Present value and other cost calculations were considered, but for various reasons Meier chose the capital recovery formula for calculations, through which he defined the cost of conserved energy *CCE*:

$$CCE = \left(\frac{I}{\Delta E}\right)\frac{r}{1-(1+r)^{-t}} \quad (1)$$

CCE was thus the cost per kWh of conserved energy corresponding to MC per MA used in this cover essay. CCE was calculated by the investment cost *I*, a discount rate *r*, the amortisation period *t*, and the quantity of conserved energy ΔE. The idea then was basically that if CCE was lower than the cost of supplying energy p_{ep}, conservation was advantageous. Through these calculations, only quadrant A options could exist and why the ranking problem was never an issue when Meier defined the model.

There were other issues with this model though. For more complex investments, such as investments in electric power generation, the cost of the investment is only part of the cost of supply. Fuel, maintenance and taxes are some examples of such costs that affect the cost of supply additional to the initial investments. Examples also exist where there are additional incomes aside from the analysed supply. Combined heat and power plants provide one such example. Here, income streams could originate from power production, district heating, waste management, and incentives for renewable energy.

Today, two other main approaches for calculating MC are dominant for CSC and MACC analysis. Both of these solve the drawbacks of using CCE as defined by Meier (1982). The first approach is to calculate total effect and the second approach is taking snapshots of a specific point in time. The ranking problem exists independently of which approach is used.

2.4.3 Aggregated

Some research using CSC/MACC aims to identify the aggregated effect of adopting options. In practice, this approach provides insights towards the total lifetime effect. Brunke and Blesl (2014) is one example where net present value calculations (NPV) are used for calculating MC and MA. The approach was thoroughly discussed by Stoft (1995), who defined CCE as:

$$CCE = \frac{TCC}{\Delta E} \quad (2)$$

The difference from Meiers definition is that Stoft divides the total conservation cost *TCC* with the quantity of conserved energy instead of only using income. To calculate TCC, Stoft uses the present value (PV) for the stream of costs *c(t)* corresponding to different options:

$$TCC = \int_0^\infty c(t)\, e^{-r\,t}\, dt \quad (3)$$

Stoft includes all associated costs such as operation and maintenance costs of an option in c(t). To calculate NPV, c(t) is substituted for the net cost *C(T)* as the negative of net cash flow *R(t)* over the amortisation period, thus accommodating both income and costs, including investments.

$$C(t) = -R(t) \quad (4)$$

It is possible to formulate MC of an option *i* through this approach as:

$$MC_i = \int_0^\infty C(t)_i\, e^{-r_i\, t_i}\, dt \quad (5)$$

Calculations of MA could be conducted in different ways. Both Mayor (1982) and Stoft (1995) use the lifetime conservation of the option to calculate ΔE. Vogt-Schilb and Hallegatte (2014) suggest including implementation time to allow comparison of short- and long-term actions. By using equation 5, this approach enables accounting for dynamic price scenarios.

2.4.4 Specific snapshot

The other dominant approach provides a snapshot in time. This could, for example, be the marginal annual emissions and production costs by investing in renewable electric power production in 2020. The difference between the aggregated approach is that the specific approach allows one to analyse a specific point in time or a specific scenario, for example the specified abatement goal of EU reach specific annual level of emissions in 2020 compared to 1990.

Kesicki (2012) uses a reference scenario in calculations of MC and MA for the UK. This is also the approach used for Papers I, II and III. While the underlying calculations could hold different complexity[10], they are simplified:

$$MC_i = TC_a - TC_b \quad (6)$$

$$MA_i = E_b - E_a \quad (7)$$

The marginal cost is thus calculated by subtracting the net total cost (TC), including operational costs, fuel costs, incomes etc, before implementation (b) from the TC after implementation (a). Investments are possible to include through amortisation of the period and cost of capital. A negative MC exists when TC is lower after implementation of an option. Similarly, but in reversed order, MA is calculated by subtracting the level of emissions (given a MACC context, for CSC included is power consumed) before implementation with the levels after implementation.

The snapshot approach has been discussed in Kesicki and Stranchan (2011), who pointed out the drawbacks of such an approach, namely not providing information on what happens before or after the snapshot. On the other hand, an aggregated approach potentially clouds options, which become unprofitable before the end of their technical lifespan during variable price scenarios.

2.4.5 Hybrid approaches

Hybrid approaches are also used. One example is Brunke and Blesl (2014), who used a snapshot for emissions combined with aggregated costs calculated by using NPV. This provides the possibility to calculate the NPV of an investment in relation to goals such as EU goals for reducing emissions.

2.5 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,** optimising actions and investments for reaching a goal; and
- **P2,** analysing 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 5 is a reproduction of one of the original MACCs from data within Jackson's article.

[10] A myriad of computer software exist that aid calculations and/or allow simulations. In a recent review of such models, more than 68 such tools were considered (Connolly et al., 2010). All of these have different strength weaknesses and particular applications ranging from worldwide to the analysis of single buildings.

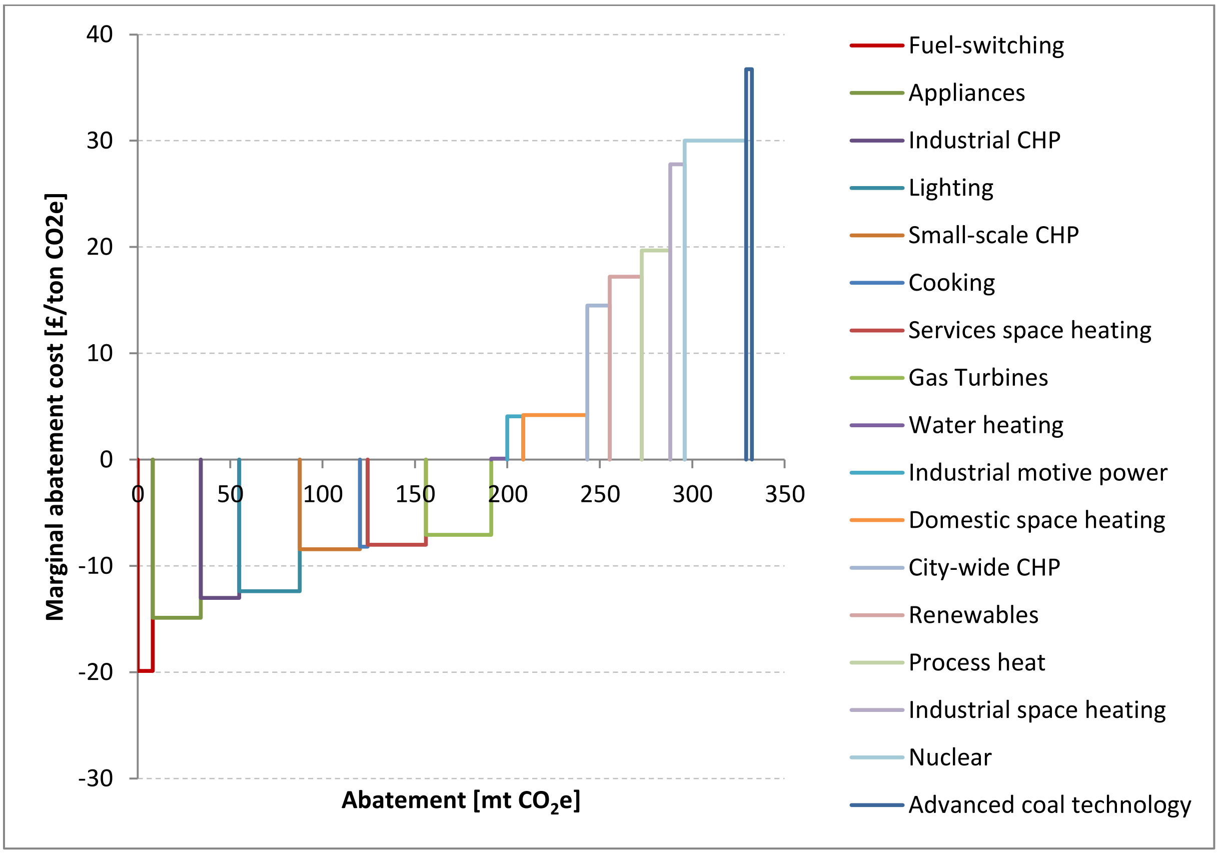

Figure 5. Recreation of one of the four original MACCs for UK by Tim Jackson (Jackson, 1991).

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 5, the idea is[11] that the option listed furthest to the left is the most 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. Furthemore, 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

[11] Assuming the ranking problem does not exist for the moment.

"renewable power technologies" and the use of "process heat", additionally becoming possible to adopt without increasing costs.

2.6 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 analysed 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 Paper I for direct option interdependency and for multi-energy systems, and indirect effects in Paper III. 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), and Levihn (2014).

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 I introduced in the introduction is not new. After Jackson (1991) presented his MACCs in *Energy Policy* in 1991, a debate between him and Wallis followed in the journal.

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 (pressurised fluidised bed combustion) versus CCGT (combined cycle gas turbine).[12] 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.

[12] PFBC is the clean coal technology used in the coal plant KVV6 (discussed in Papers I, II, III, and IV). KVV6 was constructed as a demonstration project for the PFBC technology and played an important role in competition with other technologies. This is discussed in more detail in Paper II.

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. If there was no such constrain, it is also better to prioritise 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.

For about 20 years, the discussion between Wallis and Jackson seems forgotten until Taylor, in 2012, picked up the ranking problem in an article in *Energy Policy* (Taylor, 2012). As a solution to the ranking problem, he suggests the adoption of Pareto optimisation, as this would allow optimising for the options that result in most abatement and cost reductions. However, such optimisation 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 I will discuss in the following sections.

Recently, Ward (2014) raised concern for the ranking problem in *Energy Policy* (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 Paper I, Klepper and Peterson, 2006; Delarue et al. 2010). This is a feasible approach and is part of what will be argued for by this thesis.

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 Methodology

3.1 Overall approach

The world is complex. In my view, the purpose of models and theory is to explain and predict the behaviour of different phenomena, but they will never be laws of phenomena. Models are just models, and some are good enough to fit the need of mankind.

Methodologically, an inspiration for the approach employed in this thesis has been Nobel Prize Laureate Ronald Coase. In his work, and not the least his two articles entitled "The Nature of the Firm" (Coase, 1937) and "The problem of social cost" (Coase, 1960), Coase uses logics and simple examples to provide arguments for his theses and theorems. In my view, his examples reduce the problem at hand into more feasible pieces than the more complex reality they are provided as an example of. Furthermore, in "The problem of social cost", Coase (1960) uses illustrative examples for reasoning.

Besides empirical examples, the thesis uses system simulations to provide illustrative examples and proof. Similar approaches within the field include Vogt-Shilb and Hallegatte (2014), Brunke and Blesl (2014), and Taylor (2012), to name three. The simulations have, as far as possible, been anchored in the empirics from the system it address.

The approach of this thesis is multidisciplinary and relies on the fields of energy engineering, economics and business administration. Interdisciplinary approaches incorporating social science allows for better understanding of the dynamics of energy problems and develop feasible solutions to them (Sovacool et al., 2015). Moreover, such research needs to move from technology to problem-centred. Instead of focusing on discrete technologies, research should address problems that need a solution.

In relation to financial and economic models, the issue of rationality in relation to the approach adopted in this thesis must be addressed.[13] The view adopted in this thesis is that a model could portray and suggest behaviour, and as such give advice on what is desirable to do. Independent if it is to understand what would be optimal for the market to do, or what the best investments for a single firm are. The limitation of such a perspective is that firms could pursue other goals than profit maximisation (Simon, 1972). Also, the bounds of our ability to evaluate possible outcomes of our actions puts a limit on how many possibilities we can and should evaluate and effectively consider (Simon, 1972).

3.2 Data gathering

As I stated in the foreword, writing the thesis and the papers has not been a straightforward process. Earlier, during my work as a research engineer in 2010 in a project on flexible emissions fees financed by the Nordic council of ministers, I started to question the MACC model. In my view it was not working properly and resulted in biased conclusions. One of the problems I identified early from practice was that the model did not account for interdependencies, in particular interdependencies from options outside the analysed context.

3.2.1 Papers I, II and III

During the spring of 2011, I contacted the local district heating utility AB Fortum Värme samägt med Stockholms stad with the intention of getting access to information and tools to further research the model. It ended up at the strategy analysis department within the utility, and I

[13] A sentence written by Krugman comes to mind: "Before proceeding further we should ask what aspects of reality, if any, is captured by the story we have just told" (Krugman, 1979, pp. 478).

conducted fieldwork by collecting data and performing calculations and simulations during the rest of the year and the beginning of 2012. This included collecting data on the behaviour of the existing installed production mix, as well as on considered investments and previous research related to district heating production in Stockholm. This was aided by the openness and collaboration the utility firm provided. This became the basis for the data used in Papers I, II and III, although development of the articles continued until final publication.

I gained access to all available information on what major changes and investments were considered for the utility's district heating production. I accessed to data on all of the utility's customers and its energy consumption. To gain access to the data I signed a contract of confidentiality when the project was initiated. Fortum has been extremely helpful and open, and the only thing that has been removed from the papers was a row with the expected capital cost for some considered investments. The reason to remove this was simply that one of the considered investments was decided upon but not realised, and thus Fortum did not want to disclose to their suppliers what they expected the new unit to cost.

During this time the problem of ranking negative cost options was identified and strengthened by Taylor's (2012) article, published online in late June 2012.

3.2.2 Paper IV

In 2012, a further opportunity was presented when I got involved in a project on smart metering and energy awareness. It happened that Fortum had hourly metering data of district heating consumption of all their customers available from 2006. With more than 13,000 building complexes as customers, this results in about 13 GB of raw data per year.

This big dataset was used for Paper IV, which is an explorative article, as city-wide big meter data have not been used in the context of academic research on climate change abatement and energy conservation before this paper was made. As such it presents an utterly novel source of data for addressing many energy-related issues at hand.

3.2.3 Paper V

The last appended paper was the first to be published and was based on data collected during my master thesis. The paper uses a manual quantitative content analysis methodology of letters to shareholders presented in annual reports. More information on the methodology and assumptions are presented in the paper. Although it has less in common with the other appended papers, it was essential for the process and developing knowledge of climate change in relation to firms, not the least since I manually read and quantified the content of 1,131 annual reports. Paper V also presents a significantly alternative methodological approach compared to the other papers.

4 Appended papers

The order of the compiled papers is not chronological; rather the aim is to provide a logical sequence of arguments. Paper I is the most recent journal publication, but was the second paper included in this thesis to be developed in an earlier form. It provides the MACC context of the following papers in addition to the function as an individual paper. Paper II was the last paper to be developed and provides details of the dynamics of the energy system relating to two of the investment options discussed in Paper I. Paper III extends the system dynamics aspects to a multi-energy system perspective on heat and power production, which chronologically was the fourth paper to be developed . Paper IV looks forwards to the emerging big metering data analysis trend, and thus provides an outlook for a promising methodology that could be adopted for CSC/MACC analysis. Paper V was the first paper that I developed.

4.1 Paper I

Title: Marginal abatement cost curves and abatement strategies: taking option interdependency and investments unrelated to climate change into account

Authors: Levihn, F., Nuur, C., Laestadius, S.

Journal: Energy, 2014, vol. 69, pp. 336-344.

Purpose: The purpose of this article is to develop the methodology used for expert-based MACCs during situations with option interdependency. The paper explores situations where certain alternatives condition others. Thus, the paper relates to previous discussions on option interdependency by Brunke and Biesl (2014); Vogt-Schilb and Hallegatte (2014); Morris et al. (2012); Kesicki and Eckins (2011); Beumont and Tinch (2004); Crique et al. (1999); and Stoft (1995). The contribution covers situations wherein the performance of considered abatement options is dependent on events external to the considered issue (e.g., climate change abatement in the paper).

Main findings and conclusions: The system of which abatement options are part of evolves with each implemented option. As a result some options greatly affect the performance of others. In some circumstances this includes events external to reaching the considered goal, but that likewise affect the system of which abatement options are part of. By taking the influence of later adopted options on earlier adopted into account, redundant investments and measures might be avoided. Furthermore, an iterative approach should always be used, preferably coupled with feedback mechanisms evaluating potentially changed performance of previously selected options. This might be combined with including options external to reaching the goal in the analysis, creating an overlap in the CSC/MACC.

Different options condition each other's. As such each selected option will potentially have an effect on what else is selected. The conclusions are generalisable to other least cost planning contexts such as water conservation or waste management.

The paper also includes a definition on the marginal concept as it is used in this cover essay.

4.2 Paper II

Title: Biomass and waste incineration CHP: the co-benefits of primary energy savings, reduced emissions and costs

Authors: Levihn, F., Nurr, C.

Journal: WIT Transactions on Ecology and the Environment, 2014, vol. 190, pp. 127-138.

Purpose: The focus on climate change has put other issues relating to the local environment in the shadows (Sliggers, 2004). This is problematic as many green initiatives aggregate air quality issues (Tiwary et al., 2013). This paper provides an in-depth discussion and analysis of two of the abatement options analysed in Paper I, namely the biomass CHP plant under construction called KVV8 and the proposed waste incineration CHP plant called KVV7/P7. The purpose of the article is to investigate the effects of constructing new production plants in a combined renewable and fossil energy system. In particular the effect on CO_2-, SO_x- and NO_x- emissions are discussed together with primary energy conservation.

Main findings and conclusions: The paper provides an in-depth discussion of how the south/central district heating system in Stockholm is affected by constructing the plants KVV8 and KVV7.

The paper raises an important fact as regards CO_2 versus emissions affecting the local environment. While CO_2 affects the global climate and is somewhat independent of location, SO_x and NO_x emissions are not. As such considerations of location must be considered when performing abatement. What effect emissions has on people and the local environment in turn depends on factors such as prevailing wind conditions and chimney height.

The results show that given the effect on the system, constructing the plants has a marginal effect on total SO_x and NO_x emissions from district heating production within the region. However, there might be other positive effects as the concentration of emissions is favourably moved around the city to less densely populated areas.

This is highly dependent on the competitiveness between different production facilities. Lower production costs result in more production hours. This in turn results in more of the present installed capacity being substituted. To understand the effect of new plants this must be considered.

This paper shows that given the present district heating system in Stockholm, constructing KVV8 and KVV7 would result in even relatively larger primary energy conservation than CO_2 reductions. This is much a result of substituting heat only boilers with efficient combined heat and power plants.

4.3 Paper III

Title: CO_2 emissions accounting: Whether, how and when different allocation methods should be used

Author: Levihn, F.

Journal: Energy, 2014, vol. 68, pp. 811-818.

Purpose: The issue of allocating the effect of various measures within energy systems is highly controversial (Dotzauer, 2010). Even more so when firms and their plants operate in multi-energy system contexts such as combined heat and power production. Understanding the integration of a multi-energy system allows for better system performance than if handled as separate (Mancarella, 2014). Yet, the fact that investments have a lifespan often 10 times longer than the period politicians are elected for is problematic (Johansson et al., 2007). Even if intentions are good, energy policy could have unintended consequences (Difs, 2010).

The question of allocating CO_2 emissions from changed electric power production/consumption is one such controversial issue. Yang (2013) has also made specific recommendations for how to allocate emissions in a MACC context, advocating for one possible accounting method. Paper III seeks to address how the three levels; local, regional and interregional, through the EU ETS affect the allocation of CO_2 emissions. In particular it recommends the use of an average, residual or marginal perspective on alternative production.

Main findings and conclusions: When investing in new production, efficiency or energy conservation measures, only the direct local emissions should be accounted for. For actors calculating their CO_2 footprint or comparing various options either approach might be used. Those firms included in the EU ETS should only count those emissions that are relevant to the trading scheme. For impact analysis, a marginal perspective should always be used.

In relation to MACC the paper concludes that Yang (2013) is wrong in advocating that a marginal perspective should always be used. For MACCs relating to certain policy, only emissions relating to the policy instrument should be counted. If a MACC is constructed relative to a market price on CO_2 emissions, only the direct emissions should be accounted for. Likewise, only direct emissions in control should be considered by firms and other actors who evaluate investments or other options. If instead a system-wide impact is to be understood, then a marginal perspective should be used that accounts for the dynamics between multi-energy systems.

4.4 Paper IV

Title: Big meter data analysis of the energy efficiency potential in Stockholm's building stock

Authors: Sharokni, H., Levihn, F., Brandt, N.

Journal: Energy and Buildings, 2014, vol. 78, pp. 153-164.

Purpose: There is an emerging trend to use big meter data for various kinds of analysis. In relation to the energy sector and energy conservation, big meter data research performed is limited to hourly metering data and often limited in range (see for example Tian et al., 2014; Yan et al., 2012; McLoughlin et al., 2012). In this paper, we accessed hourly metering data from about 15,000 houses and building complexes, covering 74% of all heated areas within Stockholm City and much of the surrounding region. Access to such data is scarce, and it seems that the group behind the article is presently the only academic research team in possession of it. Thus, the paper presents a novel approach and unique set of data not found elsewhere in research. As such the paper provides the first explorative step in analysing and processing this kind of data.

Main findings and conclusions: The findings show a great potential for the use of big meter data to assess different efficiency and conservation potentials. Coupled with actual production data, it is also possible to fully integrate the analysis of how energy conservation measures relate to the reduction of CO_2 emissions, which we are currently working on. For Stockholm, we also show that contrary to popular belief, the houses originating from the "million program"[14] do not constitute the buildings with worst energy performance; those belong to houses built between

[14] This is not an actual programme but rather a governmental goal and policy to build one million homes between 1965-1975. As such all houses constructed during this period are "million program" houses.

1925-1946. This confirms earlier results by Andersson et al. (2009), who previously made similar conclusions for Swedish cities other than Stockholm.

The potential to use such data for determining energy conservation potentials is enormous and opens for directed actions. Although not explicitly concluded for the CSC/MACC field, big data could potentially have a revolutionary effect on such studies.

4.5 Paper V

Title: Corporate response to climate change mitigation: what can we learn from annual reports of European industries?

Authors: Levihn, F., Nurr, C., Blomgren, H.

Journal: International Journal of Industrial Engineering and Management, 2011, vol. 2, pp. 77-86.

Purpose: The purpose of this article was to investigate how the focus on climate change issues has developed among the largest public firms in Europe during the 2000-2009. Furthermore, the analysis distinguished between the energy, petroleum, vehicle, insurance, and finance industries, respectively.

Main findings and conclusions: Before 2005 the interest was rather low, with only a marginal focus present among the energy utilities. In 2005, the petroleum industry increased its interest and in 2006 other industries followed with a larger interest in climate change issues. This interest grew until 2008, when it was pushed aside by the financial crisis. During 2008-2009, the interest was marginal within the finance and insurance sectors, and has declined for the average European firm since the financial crisis started. Growing interest was observed for the petroleum and energy industries, while it was more continues for the vehicle manufacturers.

In the paper, it is argued for that this reflects the difference in transformative pressure between different industries, with the highest pressure identified among more CO_2 intensive businesses.

5 Discussion

As the introduction outlined, this thesis addresses the problem of ranking options with a negative marginal cost in the partial equilibrium derived bottom-up CSC/MACC model. I will start by discussing Taylor's proposed solution and then provide arguments for a new solution.

5.1 Pareto optimisation as a solution to the ranking problem

The thought of Pareto optimisation 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.

5.1.1 Taking corporate behaviour into account

Pareto optimisation, 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 optimisation 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 optimisation if D is more desirable than option B with -15 in MC and 10 in MA. 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 optimisation to solve the ranking problem of CSC/MACC.

Option	MC	MA	MAC
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 optimisation, both options B and D should simultaneously be highest in merit followed by A and 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 investor invests because they expect a financial return (Stiglitz, 1993). Presently, profit maximisation/cost minimisation enables future access to capital, which in turn is a key enabler for managing future investments.

The second problem is that Pareto optimisation 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). Paper I 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 optimisation does not fulfill the requirements as good optimisation for either of the purposes P1 or P2.

5.2 Robust relative economic policy

I will leave Pareto optimisation 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[15] 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)[16] 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.

5.2.1 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, 2014). Especially 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.

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[15] Production or supply of goods or services per CO_2 emissions.

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

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 analysing 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 optimisation 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 [Paper I] [Paper II]. 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 [Paper II]. 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 analysing market reactions or optimising actions in the first place, even if the ranking problem did not exist.

5.3 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 [Paper II]. 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 minimised.

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).

Optimising 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 (see section 2.1), 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. In Paper V, we showed how the strategic focus on climate change-related issues, on average for the largest European firms, was pushed aside by economic considerations as the 2007financial crisis broke out. Likewise, during the 1980s, there was a focus on acidification and pollution of the local environment, which now has been traded for greater focus on climate change [Paper II]. My point is climate change is one matter amongst many others. Firms and nations need to perform within many different areas.

As I have taken a normative approach in this thesis, the result of using the model would not describe the exact market response but rather give insights to what would be a desired response given profit maximisation.

5.4 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 analysing the effect of different economic policy instruments, is problematic due to the ESMO effect previously discussed.

5.4.1 Managing ESMO in CSC/MACC

The model provides snapshot for a certain scenario. Both economic factors and interdependencies between adopted options affect the result [Paper I]. This is problematic if the model is used wrongly but also provides possibilities. In [Levihn, 2014] I performed a sensitivity analysis for the calculations used in Papers I, II and III. This clearly showed that due to the ESMO, robustness only existed for a certain narrow band of economic policy. Furthermore, the analysed 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 analysed scenario [Paper I].

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).

5.4.2 Relation to calculation approach

Either of the approaches outlined in sections 2.4.3 and 2.4.4 of this thesis is applicable for a scenario approach but would result in different answers. An approach where the cost flows are aggregated through net present value calculations [2.4.3] present the lifetime cost of the investment. A snapshot approach [2.4.4] on the other hand would provide insights to costs in relation to abatement for a particular period or point in time. The choice of underlying calculations is thus independent on the change in metric for ranking options.

5.4.3 A comment on scenarios and Pareto optimisation

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

The answer lies in the fundamental strength and in this case weakness of Pareto optimisation. As soon as two discrete options are on a Pareto frontier, following the conclusions from Paper I, 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.

5.5 Application to support P1 and P2

5.5.1 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 analysed 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 Paper I, 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 analysing 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.

5.5.2 Other goals and limited analytical capabilities

If firms pursue other goals than profit maximisation, using least cost planning as a pure metric is of less value. Paper I 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 optimisation 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.

6 Conclusions

In the introduction, I stated what this thesis should deliver. To start with, a theoretical contribution in solving the ranking problem of the widely used CSC/MACC model in relation to options with a negative MC. Furthermore, I made the claim that this would be conducted from a base establishing a set of arguments.

6.1 Providing the arguments

MACCs are widespread and potentially useful tools for optimising sequences of investments. As I have discussed in this report there is a fault in the metric traditionally used. Ranking options by cost per unit results in biased results for options with a negative marginal cost.

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 issue of *Energy Policy* by Ward (2014). Of these, Taylor (2012) proposed a solution in Pareto optimising the options with a negative MC.

In this cover essay, I have discussed that adopting Pareto optimisation to solve the problem would result in undesirable effects. Moreover, this optimisation is not advisable when there exists interdependencies between discrete abatement options due to the effects described in Papers I, II and III.

These dynamics between options has a further consequence. Expert-based/bottom-up CSCs and MACCs evaluating and analysing 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.

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 Paper I, 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 and understand the effect on cost and associated goals such as CO_2 abatement.

6.2 Practical implications for using bottom-up supply curves

After providing the arguments and defining a new metric for expert approaches based on the partial equilibrium model, I will now suggest how such an approach could be carried out.

1. To start with, marginal cost minimisation should be used as a metric for establishing a merit between options with a negative marginal cost. This avoids the present problem with ranking such options. Thus, it is a question of supplying enough CO_2 abatement or energy conservation, for example, under the optimisation goal of minimising costs.
2. An iterative approach taking dynamics and interactions between different possible actions should always be used. This is further explained in Paper I, together with the implications of not taking such interactions into account. The need for this approach is the main reason why Pareto optimisation does not solve the ranking problem discussed in this thesis.
3. All CSC and MACC analysis should include all economic factors affecting the decision on adopting discrete actions. For the climate change context this includes economic policy instruments such as carbon trading through the EU ETS and different environmental taxes. This is a result derived from Paper I together with Levihn (2014). Different abatement options will be affected differently by economic instruments and other price signals. This in turn affects the internal dynamics between different options. One such effect is fuel switching in energy systems, which is a result wherein one technology will be used more than another due to changed economic conditions. As a result, when and how different production units are used are affected, along with how much they interact with other production.
4. A result of point 3 above is a need for understanding the effect of whole price scenarios. To understand the effect of changed economic conditions, for example different levels of economic policy or power prices, a scenario approach must be used. By including economic policy, a consequence of the analysis of the generated CSC/MACC is that all options that for the particular scenario have a negative MC are thus profitable under that scenario. If comparisons are made with a base scenario without the change in price signals, it is possible to investigate the effect of these. A single CSC/MACC should never be used for understanding the effect of economic policy or other price signals.
5. To account for system effects, anticipated actions that do not improve towards the analysed goal should likewise be included in the analysis if they potentially affect the performance of other options [Paper I]. Although an option such as waste incineration combined heat and power results in no change or even an increase in emissions, it might likewise affect the other units and possible actions for a system in a significant manner.
6. During some circumstances, the dynamics between multiple energy systems should be accounted for. This is further discussed in Paper III, where the effect of different allocation methodologies was discussed. The choice of allocation method comes back to the purpose of the analysis. Using the wrong allocation and thus not taking system dynamics into account could, in a similar manner to reasoning by Forrester, result in "suppressing one symptom only cause trouble to burst forth at another point" (Forrester, 1971, p. 129).
7. Lastly, while not directly connected to MACC, it is important to not forget the effect of what is adopted in relation to other areas of concern such as local pollution [Paper II]. System dynamics could counterintuitively result in undesired states arising from actions that are originally based on good intention.

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 analysed 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).

6.3 Using big meter data for CSC/MACC analysis

Increasing amounts of data are collected and our computational capabilities grow. Using these vast datasets sometimes referred to as big data is promising for many applications, and the first explorative step taken in Paper IV shows no difference.

A lesson learnt is that for the data to be effective it must be effectively clustered and enable estimations of cost, energy conservation, and how it relates to CO_2 abatement. Aside from the classifications of different vintages used in Paper IV, many other clustering such as type of buildings and/or different building uses and users is thinkable, which could all give insights to effective energy conservation and climate change abatement actions. More work is needed on developing methodologies for utilising big data for this context.

For the policy context, studies like the one applied in Paper V on larger datasets would give insights to the transformative pressure on different industries.

7 Management and policy implications

In Figure 1 in the introduction to this cover essay we find a bunch of additional couplings between different areas and appended papers.

7.1 District heating in Stockholm

In Papers I-IV, different aspects relating to energy policy for the Stockholm region are covered. Today, about one quarter of the CO_2 emissions within the city is a result of the production of district heating. This is equal to the emissions from road transport within the region.

For a detailed discussion of the system, please consult the appended papers [Papers I-IV]. Some concluding points though:

- The main source of direct local CO_2 emissions is the carbon fired PFBC CHP plant KVV6 [Paper I]. This plant is highly effective, utilises a clean carbon technology with low SO_x and NO_x emissions [Paper II], and produces a comparably high amount of electric power [Paper III].
- The other main source of CO_2 emissions is waste incineration and fossil oil peak boilers [Paper II] [Paper IV].
- There is a large share of electric boilers and large-scale heat pumps within the system.
- Peak production is based on heat only boilers.

For effective energy management and policy, these four factors are the most important to take into consideration. To start with, a result of the dynamics within the system and how the present production mix looks, CO_2 abatement is not straightforward or easy.

7.1.1 System interdependencies and multi-energy systems

Due to the dynamics within the district heating system in Stockholm, decommissioning the coal-fired KVV6 would result in decreased CO_2 emissions, but also decreased electric power production, increased electricity consumption, and increased SO_x and NO_x emissions. The reason for the undesired effects is that decommissioning the plant would necessitate electric HPs and different heat only boilers to increase production. As a result, the effect on net power export to the Nordic power system from the district heating system is multiple. Given the present power production in the Nordics this is highly undesirable and could increase CO_2 emissions more than the local reductions through closing the plant [Paper III].

As a result, an efficient closing of KVV6 would need a transformation of either system. If neither of the systems are developed it is better to keep the plant operating [Paper III]. A development of the system in Stockholm enabling an efficient closure of KVV6 would be increasing the share of CHP production [Paper III].[17]

Increasing the share of CHP would, in addition to more effective reductions of CO_2 emissions from heat and electric power production, also result in a better degree of primary energy utilisation [Paper II] and reduced costs [Paper I].

7.1.2 Trading Schemes: interregional and inter-industrial dynamics

In Europe a system for trading the rights to emit CO_2 emissions has been in place for almost a decade. The idea of the system is to introduce a price on a common property resource along the

[17] In addition to KVV8 which is presently under construction.

thoughts of Pigoue (1920), but using the market mechanism to distribute burdens and resources to the most effective options available along the thoughts of Coase (1960).

While there are many different views on whether the system works, like it or not, it is the system by which the lion share of abatement within the EU is to be managed. The system sets a limit (the cap) for the total emissions within the EU and enabling trading of the right to emit under this cap. The market supposedly directs the resources to the most effective available options. An effect of this is that reduction within one industry allows another industry to increase their emissions. To lower total European emission from the sector included in the trading system, the cap must be lowered, which is also how the system is designed.

I will not dig deeper into this policy instrument in this cover essay, as it is discussed to some extent in Paper III, but I will raise a concern. The instrument is in place, and policymakers and politicians should take the dynamics imposed by the instrument into account when designing policy, even when policy is made for a local context. Otherwise there is a risk for surprise effects potentially leading to another undesired or even worse situation.

Given the dynamics within the Stockholm district heating and the additional interaction between multi-systems such as waste management, electricity, effect on the local environment, resource utilisation and carbon trading, effective climate change abatement is a complicated task.

7.2 Conserving energy, climate change and multi-energy systems

Paper IV outlined a great technological potential for reducing energy consumption in the building stock. One issue that should be taken into account, however, is the dynamics between production measures. This was to some extent covered in Paper IV but should be extended. What we do know is that ongoing production of side developments will reduce CO_2 emissions through conserving energy. This is a direct result of reduced emissions from production and is generalisable to other contexts where efforts are made to reduce the carbon footprint from production.

Climate change abatement aside there are many other reasons for conserving energy. Even if a production mix is 100% renewable, similar to the multi-energy system dynamics discussed in Paper III, resources conserved within one energy system are possible to employ to a desired cause in other energy systems. For example, conserving energy in relation to the future energy mix for district heating production in Stockholm would save different biofuels. This biomass could be employed in producing energy in another energy system with a fossil mix, thus resulting in CO_2 abatement. The effects of such developments should follow the same allocation methods analogical to what is discussed in Paper III.

7.3 On the controversy of waste incineration

If the coal plant KVV6 is decommissioned, the main source of CO_2 emissions from district heating production would shift towards waste incineration [Paper IV]. However, efficient waste incineration with flue gas cleaning is capital intensive [Paper I], which results in high fixed costs. As a result, access to capital and income from waste management, district heating and electricity production must be large enough.

Importing waste from other nations is controversial in Sweden, and it could be expected to be even more controversial in the future if waste incineration is the main source for CO_2 emissions in district heating production. Yet, for many regions the world the requirements for building efficient waste incineration CHP is not in place. For warmer regions there is not enough demand for district heating. Access to capital is also problematic in many places.

As a result, a limited amount of nations, Sweden included, have the capabilities and context in place needed for adopting CHPs in waste management. And now the reader must excuse a personal opinion: we should take pride in enabling solutions for waste management, particularly when we do it for other parts of the world that do not have the same potential as us

Paper II concluded that the effect of additional waste incineration CHP in Stockholm would have a limited effect on emissions, or even result in a slight increase. But, such new plants could help finance other more expensive abatement options in the future [Paper I]. It is a matter of interaction between multi energy systems. If the district heating network in Stockholm is viewed as one production unit contributing with electric power to the Nordic power network, and it is possible to add more electric power with only a marginal change to CO_2-emissions, then this new production, from a multi energy systems perspective on climate change, is as valuable as other CO_2 neutral production. As a result, measures taken that does not contribute to reduced CO_2-emissions in Stockholm still could contribute to reduce CO_2-emissions in the Nordics or even Europe, when the interaction between multiple energy systems is accounted for [Paper III].

8 Limitations and future research

Given the role of the model and its authoritative influence through reports such as those made by the IPCC and the widespread use by practitioners such as McKinsey & Company, attention should immediately be turned towards the effect of the ranking problem. It is at present unknown if the ranking problem has a considerable or limited effect on the conclusions in reports such as the AR5 (IPCC, 2014).

Some issues are resolved by this thesis, but it also puts its finger on some issues that need further attention. The discussion carried out by this dissertation focuses on energy conservation and CO_2 emissions abatement. A discussion on the effect on the local environment is also carried out in relation to SO_x and NO_x emissions. As I started the introduction there are many other issues of concern for both nations and firms. For investment optimisation, energy management and effective policy, many other issues must be addressed or considered. The result of this dissertation is generalisable to many other contexts, even though their respective discussion is focused on a certain area. Take the problem of allocating CO_2 emissions discussed in Paper III. The conclusions of this dissertation could easily be carried over to other areas such as waste management issues.

Other areas remain open. While this dissertation discusses the classification problem of different types of CSC/MACC, it has not been solved. This should be addressed in future research. Also, the capabilities of the model to handle option interdependencies and multiple systems interaction should be developed further. This includes a review of the private and public characteristics of each dimension considered by the model.

Furthermore, the use of big data needs further development. I encourage utilities pursuing development into energy services to consider the value of the information they possess both to themselves and the community they are part of. The conflict for producers of energy carriers to pursue energy conservation of their customers is paradoxical in many ways, but at the same time organisations such as the IEA identify energy conservation and efficiency as the single most important tool for combating climate change. The question for utilities, and the focus of future research, should be how to leverage this development, as it is likely (and desired) to happen anyway. This raises interesting problems for many different research fields, stretching from energy system analysis to strategic marketing, economics and business administration.

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