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TRADABLE PERMITS FOR GREENHOUSE GAS EMISSIONS AND INVESTMENTS IN HEAT AND POWER GENERATION

Doctoral Dissertation

Harri Laurikka

Helsinki University of Technology
Department of Mechanical Engineering
Laboratory of Energy Economics and Power Plant Engineering

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ABSTRACT OF DOCTORAL DISSERTATION

Author Harri Laurikka

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Abstract

This thesis explores how tradable greenhouse gas emission permit systems affect investments in heat and power generation. The research question is approached from a capital investor's or the regulator's perspective with six individual articles. Cap-and-trade and baseline-and-credit emissions trading systems are analyzed. The value of an emission permit and other relevant decision variables are treated as stochastic processes in a risk-adjusted framework. Models combining simulation and dynamic programming are presented to analyze single-firm problems with several stochastic variables. The approach extends the standard discounted cash flow analysis by taking into account the value of management's flexibility to adapt and revise later its decisions in response to market development. The implications are analyzed and discussed in association with several technologies. The thesis contributes to the research on emissions trading system design and on practical implications of emissions trading systems on investments in heat and power plants.

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Tradable permits for greenhouse gas emissions and investments in heat and power generation

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2. Laurikka, H., Koljonen, T., 2005. Emissions trading and investment decisions in the power sector– a case study in Finland. *Energy Policy* (In press). 12 p.

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4. Laurikka, H., 2005. Option value of gasification technology within an emissions trading scheme. *Energy Policy* (In press). 13 p.

5. Laurikka, H., 2002. Absolute or relative baselines for JI/CDM projects in the energy sector?, *Climate Policy* 2 (1), 19-33

6. Laurikka, H., Springer, U., 2003. Risk and return of project-based climate change mitigation: a portfolio approach, *Global Environmental Change* 13 (3), 207-217

Contributions of the author

Articles 1, 3, 4, and 5 are independent research carried out by the author. The author initiated Article 2, and was mainly responsible of its writing. The co-author had the responsibility of writing in Section 3. Article 6 was initiated and led by Dr. Urs Springer. The writing of the Article was carried out in collaboration. The author wrote Section 2 and contributed to the analysis of projects (Sections 3.1-3.2.) in Article 6.

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"It is hard to see how any rational man can ever invest" - John Maynard Keynes –

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The first one was the Institute for Economy and the Environment at the University of St. Gallen, where I had an opportunity to start my research in December 2000 – February 2002. I was involved in two research projects "Implementing the Kyoto Mechanisms – Contributions from Financial Institutions" (the European Commission, Specific Programme for Research, Technological Development and Demonstration; Contract No. EVK2-CT-2000-00076 and the Swiss Federal Office for Education and Science) and "Einsatz der Finanzdienstleistung Project Finance zur Förderung der Kyoto Mechanismen und eines nationalen Emissionshandels" (Ministry of the Environment Baden-Württemberg). The financial support is gratefully acknowledged. My warmest thanks go to Prof. Ernst Mohr, Dr. "JJ" Josef Janssen, Pekka Vainikka, Tomas Otterström and to my former employer Electrowatt-Ekono Oy for enabling a simultaneous research and consulting work in St. Gallen. I want to thank the "Quotenschweitzer" Dr. Urs Springer for the most useful discussions and his contribution to our joint work. I never forget the outstanding and kind help, which late Dr. Rabindra Chakraborty gave me for Article 5 of this thesis. I also want to thank Thomas Bieker, Carl-Ulrich Gminder, Kerstin Pichel, Kathi Sammer, Bernhard Raberger, and Rolf Wüstenhagen and the rest of the IWÖ staff for their contribution to my work and pleasant stay in St. Gallen.

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Helsinki, November 2005
Harri Laurikka

1. INTRODUCTION

> ”Climate change decision-making is essentially a sequential process under general uncertainty.”
>
> - Intergovernmental Panel on Climate Change (IPCC, 2001)

This thesis is about *investments* in *heat and power plants*, i.e., installations, which produce heat, electricity, cooling or their combination(s). Investments are sacrifices of current reserves for future benefits. The sacrifice takes place in the present or in the near future and is mostly relatively certain, while the reward comes later and is generally uncertain (Sharpe et al. 1999). The reward should compensate the investor for (1) the time the funds are committed, (2) the expected rate of inflation and (3) the uncertainty of the future payments (Reilly and Norton 1999). *Real investments* (in contrast to financial investments) involve some kind of tangible asset, such as land, machinery or factories (Sharpe et al. 1999). *Real investments in energy infrastructure* can broadly be divided to four categories: investments in heat and power plants; investments in transmission and distribution of electricity; investments in district heating and cooling networks; and investments in fuel supply.

Businesses compete about investment capital in global financial markets. In the electric utility industry, the current regulatory and market volatility offers a wide array of attractive investment opportunities (e.g. Bullinger and Shetty, 2004). With the regulation existing by mid-2004, it is projected that the world electricity demand will double between 2002 and 2030 (a growth rate of 2.5%/a), while most of the growth takes place in developing countries (IEA, 2004). In addition, a significant proportion of the existing capacity must be retired in many regions during that period. This implies a new capacity requirement of 4,800 GW_e globally requiring an investment of around USD 4,600 billion (Table 1). Furthermore, other final energy use in residential, services and industrial sectors is expected to grow by 16,000 TWh (37 %)[1] until 2030, implying an additional demand for heat-only plants. All in all, it is recognized that “increased investment in the energy sector, from both public and private sources, is necessary.” (EDC, 2004).

Table 1. Rough projections on the required new power generation capacity in GW.

Region	2003-2010	2011-2020	2021-2030
Finland[1]	3	4	7
OECD Europe	800[2,3] in total		
World[2]	1,100	1,700	2,000

[1] Based on Kara, 2004.
[2] Reference scenario taking into account policies and measures that had been adopted by mid-2004. Additional efforts to reach the targets of the Kyoto Protocol (see below) are not included (IEA, 2003, p. 350, 2004, p. 208).

Major factors affecting investment in the power sector in the future decades are competition, market reform, environmental constraints and access to capital (IEA, 2003, p. 354). A significant - and potentially the most significant - environmental constraint is set by climate change mitigation. In the United Nations Framework Convention on Climate Change (UNFCCC), all major greenhouse gas (GHG) emitting countries decided to stabilize “greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 2005). The UNFCCC entered into force in March 1994, and was followed by the Kyoto Protocol, which sets binding greenhouse gas emission reduction targets for specified industrialized countries. The Kyoto Protocol entered into force in February 2005. On average, the industrialized countries

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[1] Own calculation based on IEA (2004). Includes petrochemical feedstocks.

having accepted binding targets[2] to reduce their GHG emissions by 2.2% (excluding emission sinks) compared to the 1990 level by the end of the five-year period 2008-2012[3].

The Kyoto Protocol includes provisions, which enable the Parties to *trade* with different types of greenhouse gas emission *permits*[4]. The GHG emission permit market already emerged on a voluntary non-Kyoto- compatible basis in the 90's, but the volume remained small. In 2003, the trading volume was some 80 Mt and in 2004 it was 124 Mt, with an increasing momentum and growth specifically in Kyoto-compatible transactions (Lecocq and Capoor, 2005, 2004). By September 2005, the trading volume in Europe alone has been close to 200 Mt (based on GreenStream Network, 2005; Lecocq and Capoor, 2005).

The value of emission permits and other impacts caused by the trading systems are new sources of uncertainty in heat and power capacity investments. Heat and power plants typically have a long economic lifespan**,** of 20-40 years, and the prospects of climate policy beyond 2012 are unclear. Further, science on climate change gives continuously new results, which implies that the framework for policy-making may change. Therefore, the value of an emission permit can be seen as a *stochastic process*, which implies that the value of the permits evolves over time in a way that is at least in part random (Dixit and Pindyck, 1994, p. 60). More formally, a stochastic process X is a family of random variables, defined on some common probability space, indexed by an index-set I, which often represents time (Bingham and Kiesel, 2004, p. 77).

The objective of this thesis is to contribute to the understanding of the implications of these new regulatory instruments, tradable emission permits, in investments in heat and power generation. The main research question is thus how emissions trading – taking into account the stochastic value of an emission permit -- affects investment decisions. The research question can be looked at from different perspectives, such as those of:

- *a capital investor*: how does emissions trading change the expected return of an investment? How does emissions trading affect the risk of an investment? How should these investments be optimally managed?
- *the regulator* or *a non-governmental organization*: how does emissions trading and its different design options affect the volume (in number of plants or MW) and quality (fuel and technology) of investments? What are the macro-level economic, social or environmental outcomes?

In an investment problem, capital investors are typically more interested in either detailed project-level analyses or performance of portfolios of a limited number of projects. On the other hand, the regulator is more focused on aggregated analyses and (very) large portfolios, unless an individual project is very large, such as a nuclear power plant. As the total impact depends on a large number of small analyses, understanding the mechanisms of individual investment decisions is, however, the key for larger-scale analyses (Dinica, 2005). For example, Haas et al. (2004) point out the increase in investors' risk caused by regulatory uncertainty, when policies are changed. Policies implemented by the regulator can cause unforeseen policy outcomes, if the project-level decision-making is not fully perceived.

The thesis consists of individual articles, which (1) have different perspectives to the investment problem; (2) deal with different kinds of tradable permit systems (see Section 2.1. below); and (3)

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[2] A total of 156 countries (as of 16.9.2005) have ratified the Protocol, of which 34 have binding reduction targets (UNFCCC, 2005)

[3] *Average* emissions of the five-year period are used as the unit of measurement.

[4] Terminology is not homogenous, e.g., in the European Union Emissions Trading Scheme (EU ETS) permit is a *licence to operate a carbon dioxide emitting activity*. The term "permit" is used here as a generic term for different kinds of carbon assets (see e.g. Jones and Morlot, 1992; Janssen, 2001; Rosenzweig et al., 2002; and Springer, 2003).

consider different type(s) of stochastic variables related to the investment problem. The implications are analyzed and discussed in association with several technologies. The common denominator is the presence of a tradable permit system in investment problems of the energy industry.

This introductory article is organized as follows. Section 2 reviews literature on tradable permit systems in general, and Section 3 the relevant literature on investments. The focus of Section 3 is on the impacts of the tradable permit system on investments into heat and power capacity. In both sections, the contributions of this thesis relative to the body of knowledge are identified. Section 4 presents the individual articles and their key results. Concluding remarks are made in Section 5.

2. TRADABLE EMISSION PERMIT SYSTEMS

> ”Private markets are perfectly efficient only if there are no public goods, no externalities, no monopoly buyers or sellers, no increasing returns to scale, no information problems, no transaction costs, no taxes, no common property an no other ‘distortions’ between the costs paid by buyers and the benefits received by sellers.”
>
> - Fullerton and Stavins (1998): How economists see the environment

2.1 Foundations and basic concepts

A tradable permit is a limited, transferable right issued by the government to perform an activity. In the context of GHG emissions, a permit gives its holder the *right to emit a tonne* of carbon dioxide (tCO_2) or of carbon dioxide equivalent (tCO_2e) depending on the trading scheme. The goal of the provisions is to guarantee *cost-efficiency*, since the marginal GHG emission abatement costs differ among sources. The cost efficiency argument of tradable permits stems from Coase (1960), who first suggested that a market might regulate harmful effects as effectively and efficiently as a state administration. In the context of environmental regulation, Crocker (1966) and Dales (1968) were the first to consider tradable “pollution rights”. Montgomery (1972) showed that -- with certain assumptions -- a system of tradable pollution “licenses” will ensure that environmental quality standards are met at least total cost.

The first significant tradable emission permit scheme, the emissions trading policy of the Environmental Protection Agency (EPA) in the United States, began gradually in 1974. The first phase was “netting”, which allowed companies internal trading. In 1977 trading was allowed with external counterparties as well, through “offsets” (EPA, 1977; Tietenberg, 1985). Since the 1970s, tradable permit systems have been used in many environmental or resource problems ranging from air pollution[5], fisheries, water management, waste management and land use. However, tradable emission permit systems did not come into a wide-scale use until the 1990s’. In the UNFCCC, they were incorporated from the very beginning in the Article 4.2.(a, d).

Current emissions trading systems can be classified to three[6] categories: *cap-and-trade* -systems; *baseline-and-credit* (or *project-based*) trading (EPA, 2003; Janssen, 2001); and *rate-based* trading (EPA, 2003). In a cap-and-trade system, an aggregate emission *cap* is first defined for a group of polluters. Second, emission *allowances* are distributed to the group in an *initial allocation*. The initial allocation can be based on an *auction* or it can be a *free of charge allocation*, where the regulator determines the number of free allowances for each group member based on some criteria. These

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[5] see Harrison (1999) for a review on early air pollution related programs.

[6] “Bubbles”, which allow entities with multiple emissions sources to combine their total emissions targets from these multiple sources under one accounting entity, are often mentioned as emissions trading programs (e.g. IETA, 2004). However, bubbles do not necessarily allow any explicit *trading*.

criteria can range from *grandfathering* (based on historical emissions) to *benchmarking* (e.g. PWC, 2003). The year of reference can be *fixed* or it can be *updated* (e.g. Harrison and Radov, 2002). Allocation could also be *output-based* (Fischer, 2001; Lashof et al. 1997). In a *closed* emissions trading system there is a single regulatory agency to issue the allowances, whereas in an *open* emissions trading system the regulator assigns only a fraction of the total amount of allowances and considers only the welfare effects in one's jurisdiction (Böhringer and Lange, 2004). Next, members of the group can trade the allowances during *the trading period*. After the trading period, the regulator must control – possibly through an independent *verifier* - that the amount of allowances each group member has is equal to his *monitored* emissions. If this is not the case, a *penalty* may be charged. The "Acid Rain Program" in the United States, which set a national cap on sulphur dioxide (SO_2) emissions from the beginning of 1995; the Article 17 of the Kyoto Protocol; and the European Union Emissions Trading Scheme (EU ETS), which began in January 2005, are the most prominent examples of cap-and-trade systems.

In baseline-and-credit trading, the unit of trade is an *emission reduction*; also called a *credit*[7] or *an offset* (EPA, 1977). An emission reduction is generated, when an identifiable project reduces emissions compared to a predetermined reference scenario, the *baseline*. An independent third party may be requested to *validate* or *determine* that the baseline emissions have been determined in accordance with some commonly accepted *baseline methodology*. During the lifetime of the project, the operation of the project must be *monitored* so that the emission reduction can be calculated. The results can again be proved in a *verification* procedure. The most prominent examples of baseline-and-credit trading are Article 6 (*Joint Implementation, JI*) and Article 12 (*Clean Development Mechanism*, *CDM*) of the Kyoto Protocol. The Directive 2004/101/EC of the European Union linking these mechanisms to the EU ETS entered into force in November 2004.

A rate-based trading refers to an approach in which the regulating authority determines an emission rate performance standard (i.e., an amount of emissions allowed per unit of heat input or product output) for a sector (e.g., tons/kWh) and allows sources that over- and under-comply with the standard to trade credits (EPA, 2003). Corporate Average Fleet Efficiency (or CAFE) standards in the US are an example of this kind of a system: the CAFE standards allow car manufactures to make changes within their own fleet of vehicles to ensure an overall average improvement in gas mileage per vehicle sold (IETA, 2004).

2.2 Main research problems

Research problems originated by tradable emission permit systems could be classified into four categories (1) the policy instrument selection problem; (2) trading scheme selection problem; (3) trading scheme design problems; and (4) trading scheme implication problems.

Policy instrument selection problem: The first major question has been the performance of tradable permit systems as an environmental policy tool relative to other policy instruments, such as command-and-control and taxes. The main finding of Dales (1968, p. 801-802) was that an across-the-board charging scheme is "clearly the best" way to achieve a specified policy target, and a system of tradable permits "reduces administrative costs by relieving administrators of the necessity of setting the charge for rights and changing it periodically to reflect economic growth or decline". Baumol and Oates (1971) found that a fixed emission standard in a society, which produces a given output quantity with minimal costs, requires that marginal production and abatement costs are equal in all firms. This condition is fulfilled in an ideal decentralized market economy, if there is a uniform per-unit tax on emissions, i.e. a Pigouvian tax. The result implies that an emissions trading system

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[7] This term was already used in association with "netting" in the US emissions trading policy in 1974 (Hahn 1989).

may give the same result as an optimal tax set by the government to reach the standard, but only under the assumption of perfect knowledge. Weitzman (1974) established the conditions under which the expected welfare gain under a unit tax exceeds or falls short of that of a tradable permit system, in the case that the abatement costs are uncertain (for the regulator): if the marginal environmental benefit curve is steeper than the marginal abatement cost curve, then the regulator should use tradable permits, and vice versa. The analysis of Weitzman (1974) has later on been completed with, e.g., adding uncertainty of the marginal abatement costs in companies (Adar and Griffin, 1976); nonlinear instead of linear functions and multiplicative instead of additive error terms (Watson and Ridker, 1984); correlated uncertainty in functions (Stavins, 1996); incomplete enforcement (Montero, 2002); nonlinear or adjustable tax rates (Kaplow and Shawell, 2002); the stock of the pollutant and policy stringency (Hoel and Karp, 2002; Newell and Pizer, 2003).

In the control of GHG emissions, recent studies suggest that taxes dominate tradable permits as long as the benefit function is rather flat (Baldursson and von der Fehr, 2004; Hoel and Karp, 2002; IPCC, 2001; Newell and Pizer, 2003). Babiker et al (2004) argue that international emissions trading can also be welfare-decreasing due to negative terms of trade and tax effects.

On the other hand, theoretically appealing Pigouvian taxes have not been broadly introduced in practice. Several reasons have been suggested in literature, including: (1) economic actors' *resistance of new taxes* due to efficiency and competitiveness considerations (Pearce and Turner 1990, p. 96-98; Vehmas et al. 1999); (2) *lack of knowledge* of the optimal tax level (Cropper and Oates, 1992; Pearce and Turner 1990, p. 96-98); (3) the need to preserve the *status quo* in society (Pearce and Turner 1990, p. 96-98); (4) the *unwillingness to transfer capital* from the private sector to the government (McKibbin and Wilcoxen, 2002; Springer, 2003); and (5) a *regulatory gap* between economists who know theoretical virtues of Pigouvian taxes and administratives who are aware of practical difficulties in the legislation and implementation phase (Määttä, 1997, p. 15). All these except (4) apply to emissions trading (with free allocation) as well. Buchanan and Tullock (1975) have argued that firms will prefer emission standards to taxes because standards serve as a barrier to entry for new firms, thus raising company profits.

Deficiencies of both systems invoked an early interest in *hybrid approaches*, where emitters can trade permits with other emitters or buy them from the government with a trigger price (Roberts and Spence, 1976). Such an "escape hatch" or a "safety valve" has attracted also recent interest (Jacoby and Ellerman, 2004; McKibbin and Wilcoxen, 2002, 2004; Pizer 2002).

Trading scheme selection problem: the relative performance of different kinds of tradable permit systems has also aroused interest. It has been found that a baseline-and-credit system (in comparison to a cap-and-trade system) requires less regulatory effort *in the beginning* and is thus suitable for situations where institutional capacity is limited (OECD, 1999). As each project has to be evaluated separately, however, the running costs of the system are higher. Overall, the transaction costs of cap-and-trade systems are considered lower than those of baseline-and-credit trading (Tietenberg 1992, Tietenberg et al. 1999, EPA, 2003), although this might be case-dependent (Woerdman, 2001).

Trading scheme design problems: Noll (1982) identified four major design problems related to tradable emission permit systems: (1) liquidity of the market; (2) market concentration and competition; (3) sensitivity of the environmental quality to the geographic dimension of emissions and (4) the amount of flexibility the regulator has to alter the total amount of emissions. The third point is obviously not relevant in the context of carbon dioxide emissions, as they are uniformly mixed. The regulator has design *features* to attack the problems above: permit life, market definition, market initialization (i.e. the initial allocation) and provisions for market operation (Noll, 1982).

Since Dales (1968) it has been suggested that the regulators could have different vintages of permits: some perpetual, some of longer and some of short-term duration. More risk-averse firms could then sell short-term allowances and buy long-term allowances (Noll, 1982). Tietenberg (1985) argued that the vintage should depend on the type of pollutant. In the context of the EU ETS, for example, the idea of using different vintages has materialized: there are Allowances, Emission Reduction Units (ERUs) and Certified Emission Reductions (CERs), which all have different vintages.

Noll (1982) noted "trades in thin markets usually have high transaction costs and produce noisy price signals. This can prevent markets from being substantially more efficient than a system of source-specific standards". Transaction costs may lead to a significant exaggeration of cost-competitiveness of emissions trading (Stavins, 1995). Transaction cost source categories for market participants can be summarized as (1) search and information; (2) bargaining and decision; (3) monitoring and enforcement; (4) costs of regulatory delay and (5) indirect costs associated with uncertainty of completing a trade (Stavins, 1996). In addition, there are political transaction costs outside the group of market participants (Betz, 2003).

Recently, a lot of attention has been paid to transaction costs particularly in the case of baseline-and-credit systems, such as JI and the CDM (e.g. Fichtner et al. 2003; Krey, 2005; Michaelowa and Jotzo, 2005). It has been found that transaction costs in these mechanisms do not strongly depend on project size (e.g. Fichtner et al. 2003; Krey, 2005). The current experience suggests transaction costs ranging from USD 60,000 to USD 480,000 without monitoring and verification for large-scale projects (Krey, 2005; PCF 2003) or around 15% of the total procurement costs (without the costs of learning) in JI/CDM (MTI, 2005, p. 21).

Another problem in the market definition in terms of greenhouse gases is the question whether the trading scheme should be targeted for upstream sources (e.g. fuel suppliers) or downstream sources (e.g. utilities) (e.g. Dudek and Tietenberg, 1992; Mohr, 1992). In practice, most current GHG emissions trading schemes tend to rely on downstream schemes.

After the interest in tradable permit systems in the 70s', the initial allocation methods of cap-and-trade systems became a natural research topic (e.g. Eheart et al. 1980). Dales (1968) originally thought that the government would "issue x pollution rights and put them up for sale". From the very first emissions trading schemes (EPA emissions trading policy, Fox River, Lead trading, Dillon Reservoir), to the current systems the majority of emission allowances have, in reality, been given to companies free of charge (Hahn, 1989; Hasselknippe, 2003). Lyon (1982) studied different allocation systems with a simulation, and found a trade-off between decreasing the financial burden of rights purchases and removing the incentives for strategic behaviour. The effect of the initial allocation on market concentration was first considered in the research of Robert Hahn (e.g. Hahn 1984).

Experience from the last few decades in the initial allocation methods is summarized in Harrison and Radov (2002). Examples on the recent work on initial allocation include Montero (1998) arguing that in the presence of transaction costs and uncertainty, the initial allocation may not be neutral in terms of efficiency. Montero (2000) studies the optimal allocation with the presence of a voluntary opt-in opportunity for non-affected firms. Burtraw et al. (2001) compare grandfathering, auction and output-based allocation with a detailed electricity market model, and find the auction to have the lowest societal cost. Liski (2001) stresses the importance of the initial allocation on the transaction costs in a cap-and-trade scheme with a model, where trading costs develop endogenously as a function of the market size. Baron and Bygrave (2002) consider linking of emissions trading schemes with different allocation methods, and find little evidence suggesting major problems. Böhringer and Lange (2004) show that an optimal free allocation of allowances (including updating) depends on whether the emissions trading system is open or closed. Bode (2005) analyzes different allocation options (including updating) in multi-period emissions trading, and finds that utilities should have different preferences depending on the fuel used. Articles 2 and 3 of this thesis discuss the impacts of the initial allocation method (grandfathering vs. auction) on the risk of a capital investor.

In baseline-and-credit systems, the concept of baseline emissions is closely linked to the requirement of *additionality* of emission reductions as stated e.g. by Articles 6.1.(b) and 12.5 (c) of the Kyoto Protocol. The determination of additionality and the baseline are critical to the environmental objectives of a baseline-and-credit system. Discussion on the practical implementation of these concepts began during the Activities Implemented Jointly (AIJ) pilot phase of the UNFCCC (e.g. Carter, 1997; IEA, 1997; Jepma, 1995; Michaelowa, 1998; Rentz, 1998), though the concept had already been in use in demand-side management projects in the US; in control of ozone depleting substances; and in the Global Enviroment Facilitity (GEF) (Sugiyama and Michaelowa, 1999). After the Kyoto Protocol, specific "additionality tests" ranging from financial assessments to market barrier analyses, and to examination of planning documents have been developed and discussed (Bode and Michaelowa 2003; Greiner and Michaelowa, 2003; PROBASE, 2003). Different insights and opinions were consolidated into a voluntary tool for the demonstration and assessment of additionality in December 2004 (CDM EB, 2004).

Baseline approaches have been an intensive research area during the last decade (see e.g. Chomitz, 1998; Ellis and Bosi, 1999; Ellis et al., 2001; Gustavsson et al., 2000; Kartha et al., 2004; Lazarus et al., 2001; OECD/IEA, 2000; PROBASE, 2003). A central question has been whether to use project-specific, multi-project or hybrid baselines (Ellis and Bosi, 1999; Ellis et al., 2001; OECD/IEA, 2000), and how to put multi-project baselines into practice (BASE 2003; Ellis et al., 2001; Hargrave et al., 1998; Kartha et al., 2004; PROBASE, 2003; Sathaye et al. 2004). Other problems have been baseline dynamics (i.e. should the baseline be deterministic, or to some extent dynamic or revisable) and data aggregation in multi-project baselines (e.g. Baumert, 1999; Gustavsson et al., 2000; Lazarus et al., 2001). There has also been discussion on whether baselines should be expressed in absolute (in tCO_2e) or relative terms (in tCO_2e per unit of production e.g. kWh), and what kind of implications this might have for different stakeholders (e.g. Baumert, 1999; Ellis et al., 2001; Janssen, 2001; Willems, 2000). Article 5 of this thesis contributed to the last point focusing specifically on accuracy of emission reductions and manageability of GHG emission balances. Quantity risk implications of different baseline methodologies are also discussed in Article 6.

Other research problems in trading scheme design, which are not discussed here are e.g. banking (e.g. Rubin and Kling, 1993; Rubin, 1996); borrowing (Rubin, 1996); links to other trading schemes (e.g. Baron and Bygrave, 2002; Bygrave and Bosi, 2004); and mechanisms for monitoring and non-compliance (e.g. Tietenberg, 1985; Dudek and Tietenberg, 1992; Zhang, 1999).

Trading scheme implication problems: numerous stakeholders of tradable permit systems are interested in the implications of a particular trading scheme. The focus of the implications studied can differ widely, for example: financial (e.g. Janssen, 2001; Rong and Lahdelma, 2005); economic (e.g. Peterson and Klepper 2004); technological (e.g. Barreto and Kypreos, 2004); environmental (e.g. van Vuuren et al. 2005); and social (e.g. de Motta 2004). The amount of literature in this area is enormous due to the preparation to the recent wide-scale use of trading schemes. Articles 1 to 4 and 6 of this thesis mainly belong to this category and focus on financial aspects.

3. IMPACTS ON INVESTMENTS IN HEAT AND POWER GENERATION

> ”Over half the respondents felt that emissions trading would have a ‘significant impact’ on the fuel mix of future power generation.”
>
> - Ernst & Young survey of 200+ of the largest European companies involved with the European Union Emissions Trading Scheme, June 2004

3.1 Investment decision process

Real investment *decisions* are often strategic due to the substantial amount of capital involved. The shift towards decentralization and profit maximization in power systems is likely to incur a higher degree of strategic decision-making (Botterud 2003, p. 17; Hobbs, 1995). Strategic decisions of individual companies result from processes which are affected by environmental, organizational and decision-specific factors (Rajagopalan et al. 1993). Decision processes involving evaluation of capital expenditure typically consist of at least four steps: (1) Identification of spending proposals; (2) Quantitative analysis of the incremental cash flows; (3) Qualitative issues which cannot be fitted into the cash flows calculus; and (4) Making the decision (Shank, 1996). When companies consider capacity expansion, they can have a make-or-buy decision i.e. an acquisition may be an alternative to a construction project (e.g. Yan, 2001). Article I of this thesis discusses the impacts of climate policy instruments, such as tradable emission permits, on the investment decision process.

Research on investment decision processes can be either descriptive or prescriptive[8] (Clemen and Reilly, 2001, p. 4). This thesis is definitely on the prescriptive side, and focuses on the quantitative investment appraisal. Botterud (2003, p. 19) notes that decision support models for investment decision processes can equally be either prescriptive or descriptive. Prescriptive models are based on optimisation, and the main purpose is to find the optimal investment strategy. The purpose of descriptive models is to increase a decision maker’s knowledge through simulation of the future system development under a set of different assumptions. All articles of this thesis apply descriptive models.

Different analytical tools are deployed for different levels of uncertainty: when uncertainty increases, managers tend to prefer more qualitative tools (Alessandri et al., 2004; Courtney et al., 1997). Empirical studies show that uncertainty tends to dominate to risk[9] in decision-making (Alessandri et al. 2004; March and Shapira, 1987). This is in line with Myers (2001) who states that finance theory has had “scant impact on strategic planning”, although “strategic planning needs finance”. He offers three more specific explanations to this “gap”: (1) finance theory and traditional approaches to strategic planning may be kept apart by differences in language and “culture”; (2) discounted cash flow analysis may have been misused, and consequently not accepted in strategic applications; and (3) discounted cash flow analysis may fail in strategic applications even if it is properly applied. In particular, there is a bias against long-term projects (Myers, 2001). Below, the last two points are elaborated in more detail.

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[8] Prescriptive research is interested in helping people make better decisions, whereas descriptive research focuses on how people actually make decisions (Clemen and Reilly, 2001, p. 15).

[9] Uncertainty and risk are often differentiated in capital budgeting: while risk refers to a consequence and a *probability* for the consequence, uncertainty refers to a situation where the decision-maker is unable to assign probabilities to consequences (e.g. Alessandri et al. 2004; Knight, 1921; March and Simon, 1958)

3.2 Theories and tools for quantitative investment appraisal in heat and power generation

The theory of quantitative investment appraisal is based on some groundbreaking results in the 20th century. Fisher (1907) was the first to explicitly propose that the value of an asset can be estimated by discounting its future cash flows with an appropriate rate. There is thus a "time value of money", which says that the same amount of money is worth more today than it is tomorrow. However, Fisher (1907) did not develop a methodology for the selection of 'an appropriate rate'. Markowitz (1952) proposed to measure the *risk* of a security by the variance of its returns, and presented a rule how investors would *strike a balance between risk and return*, when they choose assets in a portfolio. With that rule, investors can form *efficient portfolios*, which either maximize the return for a given level of risk or minimize the risk needed for a given level of return. A seminal paper by Modigliani and Miller (1958) stated the irrelevance of capital structure in investment decisions. Sharpe (1964) and Lintner (1965) introduced the Capital Asset Pricing Model (CAPM), which suggests that in a market equilibrium, the expected risk premium on stock depends only on the risk premium of a *market portfolio* and *beta*, the covariance of the stock return with the market portfolio divided by the variance of the market portfolio.

Standard *techniques* of quantitative investment appraisal in business today are the payback time method, the internal rate of return (IRR) and the Net Present Value (NPV) rule (e.g. Graham and Harvey, 2001; Sandahl and Sjögren, 2003). There is some evidence that this is the case also in heat and power generation (Laurikka and Pirilä, 2005; Sandoff, 2003). The relevance and adequacy of these techniques have been questioned in the so-called "new view of investment" or "real option(s) valuation" (see e.g. Dixit and Pindyck, 1994; Schwartz and Trigeorgis, 2001; Trigeorgis, 1995, for review). The central argument is that the standard techniques fail to capture management's flexibility[10] to adapt and revise later its decisions in response to market development. This failure results from the fact that investments are seldom *"now-or-never"* opportunities and they often are at least partly *irreversible*.

The modern theory of investment starting from McDonald and Siegel (1985) and Brennan and Schwartz (1985) has extended the revolutionary discoveries of Black and Scholes (1972) and Merton (1973) on financial option pricing to valuation of real investments. Black and Scholes (1972) derived their famous formula based on several assumptions, the most important of which are: (1) an opportunity to set up a continuously hedged position in the derivative and the stock that is riskless i.e. has the same payoff in all states of the world; (2) arbitrage-free markets, in which the price of this portfolio and the risk-free asset must be equal; and (3) log-normal distributions of possible stock prices at the end of any finite interval. When valuing a derivative dependent on a stock price, it is possible to assume that the world is *risk neutral* i.e. the utility functions of all investors are in the form $U(x) = ax$, where x is the wealth variable; a is constant; and no account for risk is made[11]. This implies that it is (technically) possible to assume that the expected rate of return on any asset is the risk-free rate. Thus, even though risk premiums exist for assets, their determination is unnecessary in valuing the option.

When contingent claims analysis as above is applied on real investment opportunities, it is crucial to find an appropriate twin asset or a portfolio of traded securities that has the same risk character that the firm would own if the option was exercised. In that case the project cash flows are replicated, the

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[10] Ku (1995) differentiates between *active* flexibility referring to the ability to react to change (i.e. real options), and *passive* flexibility or robustness referring to a state of being, such as a resistance or an immunity to change.

[11] Most real investors tend to be *risk averse* as first suggested by Friedman and Savage (1948).

market is *complete* and it is possible to find unique real option values for each asset. This may often be tricky (e.g. Teisberg, 1995), and in practice heat and power generators operate in incomplete markets (Hsu, 1998; OECD/IEA, 2003, p. 45; Vehviläinen, 2004). In incomplete markets the values of investments depend on various factors, such as (1) the investor's preference model; (2) available budget; (3) other assets affecting the portfolio risk; and (4) alternative investment opportunities (Gustafsson, 2004). The value of the real option must therefore be frequently estimated in a risk-adjusted framework with either dynamic programming, simulation or by adjusting the drift of the stochastic processes applied in partial differential equations with the risk premium (Amram and Kulatilaka, 1999; Dixit and Pindyck, 1994, p. 124; Schwartz and Trigeorgis, 2001, p 3.; Teisberg, 1995). Incompleteness of the input and output factor markets is also an implicit assumption of all Articles of this thesis. Articles 2 to 4 estimate the value of real options using dynamic discounted cash flow analysis (see Teisberg, 1995) i.e. simulation and, to some extent, dynamic programming.

Real investments differ from financial investments due to competitive interaction: many investments are at least to some degree interlinked through industry demand and supply (Murto, 2003). The effects of competition can be approached mathematically e.g. with system dynamic models or multi-agent modelling. In oligopolistic settings, a game theoretic approach is needed, which has implications for real options analysis as well (e.g. Murto, 2003; Keppo and Lu, 2003; Grenadier, 2000). The Articles of this thesis do not explicitly take into account strategic interaction. Instead, companies considering investments are assumed to be price-takers. This implies that the investment is small compared to the total market size *and* cannot as such be easily replicated by the organization considering investment. However, some implicit assumptions on the relationship of aggregate investment behaviour and prevailing electricity and allowance market prices are made in Articles 2 to 4.

In a price-taker setting, understanding the behavior of market prices of input and output factors is often decisive in quantitative investment appraisals. The most relevant market prices for studying energy projects have been electricity and fuel prices. Modeling of electricity and other commodity spot prices can be distinguished into two categories: (1) statistical or econometric models, which aim at direct modeling of the stochastic processes that represent prices; and (2) fundamental or structural models, which build the price processes based on equilibrium models for the market in question (Vehviläinen, 2004). Literature concerning real options is mainly based on the application of statistical models. Vehviläinen (2004) argues that the special characteristics of electricity markets are better captured with fundamental models. On the other hand, their usefulness for *long-term* modeling may be questioned due to the forecasting problems of explanatory variables, such as investment and production capacity and determinants of demand (Pindyck, 1999). Articles 2 to 4 of the thesis combine features of statistical and fundamental approaches: the price processes are modeled directly, but results of fundamental models are used to model the relationship of the market price of electricity and the emission allowance price. The reason for this is the available additional information compared to a purely statistical approach.

The most commonly used price model in applications of real option theory is the Geometric Brownian Motion (GBM) (which is characterized by a constant growth rate combined with a variance increasing in proportion to time[12]. As noted above, GBM is the price model underlying the seminal work of Black and Scholes (1973), and it has been used[13] in papers dealing with energy sector as well (Cavus, 2001; Hsu, 1998; Kumbaroglu et al., 2004; Murto, 2003; Nakamura et al., 2005; Teisberg, 1993, 1994; Venetsanos et al. 2002).

Several researchers have found that commodity spot prices in general cannot be adequately represented by GBM, since in an equilibrium setting, high prices increase supply and low prices

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[12] For an introduction to stochastic processes, see e.g. Dixit and Pindyck (1994)

[13] Either referring to the value of the project, or to the commodity price.

increase demand (e.g. Bhattacharya, 1978; Cortazar and Schwartz, 1994; Gibson and Schwartz, 1990; Laughton and Jacoby, 1995; Lund, 1993; Sarkar, 2003; Schwartz, 1997). In contrast, Metcalf and Hasset (1995) argue that cumulative investment is generally unaffected by the use of mean reversion rather than GBM. Pindyck (1999) uses a long time series for oil, coal and gas prices, and confirms mean reversion, but argues that reversion is so slow that for purposes of making investment decisions, one could just as well treat the price as GBM.

There are several differences between electricity and many other commodities, such as non-storability, high volatility, non-existence of the usual cash-and-carry arbitrage, the high number and varying characteristics of generating technologies, “price spikes” due to constraints in transmission capacity; and seasonal patterns (e.g. Deng, 1999; Deng and Jiang, 2004; Koekebakker, 2001). A number of statistical models have been developed to reflect these features (for a review, see e.g. Deng and Jiang, 2004; Vehviläinen, 2004). Authors have typically found mean reversion also in electricity prices (e.g. Deng and Jiang, 2004; Simonsen, 2003; Weron and Przybyłowicz, 2000; White et al., 2000). The unit of analysis has typically been the behaviour of an hourly or a daily price.

Articles 2 to 4 of this thesis take a *conservative* approach to real option valuation, applying a simple one-factor mean-reverting model, the logarithmic Ornstein-Uhlenbeck (OU) process in modelling the relevant long-term commodity prices. The speed of mean reversion is a parameter in this process, which makes the approach more *flexible* than a simple GBM concerning different views about the process characteristics. In the case of electricity, the logarithmic OU process applies to the annual average price of electricity. The seasonal fluctuation in electricity prices is taken into account through a fixed function based on historical price data of several years. Articles 3 and 4 depart from strict OU processes and allow a lognormal price distribution, where the expected value and the variance are comparable to a logarithmic OU process.

3.3 Implications of tradable emission permit systems on investment

Tradable emission permits create additional regulatory uncertainty in the quantitative investment appraisal of a project. Effects of regulation (in general) on investment decisions of companies have been studied e.g. by Teisberg (1993, 1994), who analyzes a hypothetical investment in a power plant project taking into account the uncertainty about the regulatory outcome of a completed project. She finds that regulation may cause asymmetric uncertainty to the value of a project, which implies that a higher degree of uncertainty may decrease the value of an investment opportunity. Pindyck (1993) analyzes the impact of regulatory and technical uncertainties on an investment in a nuclear power plant. The regulatory uncertainty is understood as uncertainty in input prices (labor, land, and materials). Liski (1997) studies the interplay of economic instruments of environmental policy (including emissions trading) and companies’ long-run compliance strategies in a fully dynamic framework. Klingelhöfer (2004) provides a general approach to evaluating all kinds of investments within a tradable emission permit system using state pricing and production theory.

Literature focusing specifically on implications of emissions trading schemes on investment in heat and power generation can be classified as: (1) literature focusing only on permit related cash flow and (2) literature focusing on total cashflow. The Articles of this thesis contribute to both research streams as discussed below.

Early contribution in the first category is Edleson and Reinhardt (1995) who studied an investment problem related to trading in SO_2 emission allowances in a coal power plant. The plant operator could either continue as before and buy the allowances needed; overcomply by installing a scrubber and sell allowances; or switch to low-sulphur coal. A real options analysis using a binomial tree for the allowance price was applied to solve the problem. Spangardt et al. (2003) apply a logarithmic Ornstein-Uhlenbeck process to support make-or-buy decisions in the emissions market, and take into account project risks of technical emissions reduction. Their model can provide an efficiency frontier from several different solutions with different profit and risk levels. De Jong and Oosterom (2004) apply a binomial model to a GHG emission reduction project, such as an efficiency improvement in an existing power plant. They assume that full-load hours of the power plant can be perfectly estimated. Kiriyama and Suzuki (2004) compare the value of an investment in nuclear power, wind power and photovoltaics in 2010 using a GBM for the value of a CO_2 emission credit. They focus on determining when it is optimal to commit to investments in emissions reduction (through less-emission intensive plants) taking into account the impact on the emissions stock, which is subject to scientific uncertainty.

Risk management of climate change mitigation projects, such as energy projects, have been studied e.g. by Janssen (2001), Springer (2003) and Article 6 of this thesis. Their analysis and conclusions are based on an assumption that investment in GHG emission abatement is not equal to an equity investment in that project activity. There should thus be an external investor, who pays the additional costs due to GHG abatement and obtains the emission permits as the return: a “GHG investor”, such as a carbon fund. The risks identified and their management is therefore focused exclusively on direct emission permit related risks, such as the permit price, the permit quantity and the abatement cost risk. Practical long-term relevance of such an arrangement remains to be seen. For example, most JI/CDM projects have so far been implemented with Emission Reduction Purchase Agreements (ERPA) where the external party simply *buys* the emission permits generated (with a potential prepayment and related sanctions for the seller in the case of non-delivery).

There is a growing, recent literature on the second category. Reinaud (2003) explores how investment decisions in the power sector may be modified with the introduction of CO_2 emission allowances. She examines both short-term and long-term impacts through a simplified aggregate level analysis ignoring any plant specificities. The analysis on long-term impacts is based on levelised cost methodology, which does not necessarily take into account the value of real options. The results show that the level at which switching from coal to gas occurs is around €19/tCO_2 on the average. De Leyva and Lekander (2003) discuss the impacts of the EU ETS on power producers in Europe, based on a bottom-up energy system model. Regional level analyses (in Finland) have been made e.g. by Electrowatt-Ekono (2002, 2003b). Articles 2 to 4 present regional level case studies on investments based on dynamic DCF analysis, which takes into account the value of selected real options involved (see Section 3.2).

Dobbe et al. (2003) and Näsäkkälä and Fleten (2004a, 2004b) analyze investments in gas-fired power plants under uncertainty with the real options approach. Lambie (2002) makes a similar analysis on a coal-fired plant. These papers assume that power companies generate electricity with the explored power plants, if the spark spread, the difference between price of electricity and the fuel cost, denoted with S, exceeds “emission cost”, denoted with E, which is (technically[14]) assumed constant. Näsäkkälä and Fleten (2004a, 2004b) however differentiate with base-load and peak–load plants: the former are assumed to generate electricity irrespective of the market prices due to inflexibility in gas inflow, while the latter produce electricity if $S > E$. Lambie (2002) models the net returns (i.e. variable returns minus variable costs) with a GBM. Dobbe et al. (2003) model futures prices of gas end electricity with mean-reverting processes similarly to Deng et al. (2001), while Näsäkkälä and Fleten (2004a, 2004b) model the spark spread through a sum of short-term deviations following an OU process and equilibrium price following an arithmetic (since the spark spread can become negative) Brownian motion with drift.

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[14] Lambie (2002) notes however “while uncertainty was not attributed to the price of permits in this example it will exist and, as suggested earlier, should increase the value of the option to invest.” Dobbe et al. (2003) and Näsäkkälä and Fleten (2004a) give similar comments.

The Articles of this thesis extend this research to emissions trading i.e. Articles 1 to 4 explicitly deal with the uncertainty in the price of emission permits, the number of free allowances and the linkage between emission allowance and electricity spot prices. In addition there are some other differences with these. The information given by forward prices is not explicitly utilized, though this can be done with the models presented. Gas-fired power plants are (always) assumed to have a real option to alter operating scale i.e. there are either no take-or-pay contracts, or there is a liquid secondary gas market[15]. Second, Articles 2 to 4 model all relevant price processes so that the volatility in spot prices is either constant or bounded, which is a more conservative approach to valuation than an arithmetic Brownian motion with drift. As a terminological difference, Articles 1 to 4 treat the cost of emission allowances and operation and maintenance costs *in* the spark spread (electricity is produced in any regulatory framework, if $S > 0$).

De Jong and Oosterom (2004) discuss combination of power, fuel and allowance price uncertainties in a very similar way to Article 2. They present a formula for an “Emission spark spread”, but do not explicitly discuss the relation of power and allowance prices or the role of initial allocation of allowances. They also come to the conclusion that “traditional investment analysis needs to be augmented with emission costs; the absolute level as well as its volatility”.

Sarkis and Tamarkin (2004) apply real options analysis to value a photovoltaic investment. They model two kinds of uncertainty, the exercise price of the technology and the emission allowance price, with a two-variable binomial lattice. The stochastic cost of photovoltaic technology is compared to the deterministic cost of conventional electricity with a stochastic value for emission permits. Weber (2004) applies a backward induction approach similar to real option theory to model the value of power plants in a long-term perspective, with uncertain allowance and fuel prices. He notes that a real options approach is desirable, but in this context “complicated by the possibilities of fuel switching with endogenous output prices and simultaneous uncertainties on loads, fuel prices, technologies and policies….therefore, future electricity prices and investments have to be treated simultaneously, thinking of a transition toward (stochastic) long-term price equilibrium”. Weber’s (2004) approach differs from conventional applications of real options theory in that prices are treated as endogenous. Articles 2 to 4 of this thesis treat the price of electricity without emissions trading as exogenous, but derive the price *increase* due to emissions trading endogenously from the results of energy system models, to estimate the future price of electricity in the Nordic market (ECON, 2004; Electrowatt-Ekono, 2003a; Koljonen et al. 2004). Similarly to Weber (2004) and Sarkis and Tamarkin (2004), Article 2 considers two stochastic variables (price of electricity and allowance price). Articles 3 and 4 both have 4-5 stochastic prices, which are dealt with simultaneously.

Rong and Lahdelma (2005) study the impacts of CO_2 emissions trading on the risk of expansion planning of combined heat and power generation. They model uncertainty through 20 scenarios that can be considered as a sample of the joint probability distribution of different stochastic parameters, such as the price of electricity, allowance price and heat demand. In each scenario, they solve a deterministic optimization model, which can take into account real options related to operation, such as the option to switch fuel. Allowance price is modeled using Brownian motion with a price range. The price of electricity is weakly correlated with heat demand and allowance price. The risk level is measured through the standard deviation of the profit. The approach to the measurement of risk is similar to Article 3 of this thesis. The optimization of the CHP plant operation is similar to Article 4 though more detailed. Article 4 in addition considers the value of a sequential investment in a stochastic framework.

Weidlich et al. (2004) explore implications of emissions trading through an agent-based model, in which different actors of the energy market are modeled independently as rational entities (i.e. agents). The model enables investigation of the interplay between different agents and market

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[15] In Finland, a secondary gas market has been functional since March 2001.

dynamics (e.g. learning). The results of real option based analyses of single agents making assumptions about the markets (Articles 1 to 4) and multi-agent based analyses making assumptions about the behavior of single agents are obviously interrelated.

4. THESIS

The thesis consists of six individual articles, which are briefly described in this section. The articles take different perspectives to the research question, focus on different tradable permit systems and consider diverse stochastic variables at varying level of quantification and detail (Table 2).

Table 2. Perspective and focus of the Articles.

Article	Perspective	Tradable emission permit system	Stochastic variables considered
Article 1	Capital investor	Cap-and-trade / Baseline-and-credit	Several (qualitative)
Article 2	Capital investor	Cap-and-trade	Price of electricity Price of emission allowance
Article 3	Capital investor	Cap-and-trade	Price of electricity Price of emission allowance Price of gas Rainfall Wind speed
Article 4	Capital investor	Cap-and-trade	Price of electricity Price of emission allowance Price of gas Price of heavy-fuel-oil Price of coal Price of biomass fuel
Article 5	Regulator	Baseline-and-credit	Project output
Article 6	Capital investor (exotic)	Baseline-and-credit	Credit quantity

(1) The impact of climate policy on heat and power capacity investment decisions

The economic lifetime of an investment in heat and power capacity typically ranges from 20-40 years. During the lifetime, different instruments of climate policy can influence the cash flows of the plant and thus its viability. Such instruments can range from problem-specific tradable emission permits to more general policy instruments, such as taxation and subsidies.

Article 1 explores the mechanisms through which climate policy instruments affect heat and power capacity investment decisions through a literature survey. Both cap-and-trade and baseline-and-credit emissions trading systems are therefore included. The perspective is that of a capital investor. First, the role of climate policy instruments in an investment decision process is analysed. The starting point is a framework of Rajagopalan et al. (1993) for strategic decisions, which is used to identify channels through which climate policy instruments change investment decisions. The decision process is split to four broad steps following Shank (1996): (1) Identification of spending proposals; (2) Quantitative analysis of the incremental cashflows; (3) Qualitative issues which cannot be fitted into the cash flows calculus; and (4) Making the decision. The way how thinking about decision-making in the context of heat and power generation has changed during the last few decades is briefly discussed. It is concluded that climate policy has significantly increased uncertainty, which results in a higher value for flexibility in its different forms.

In the second part, a closer look is taken to the quantitative investment appraisal from the Net Present Value framework. The impact of climate policy instruments on the initial investment, on the annual cashflows and on the discount rate are analysed, taking into account the flexibility aspects, i.e. how flexibility can help to cope with the impacts. Flexibility characteristics of some existing heat and power generation technologies are discussed and compared with each other.

Heat and power generation technologies show significant structural differences in flexibility to stochastic changes in climate policy instruments. Whereas some technologies provide active flexibility through options to alter operating scale and to switch between fuels or products, others provide passive flexibility (robustness). Active flexibility can be taken into account through the real option theory in the investment decision process. Robustness either creates upside potential in annual cashflows or provides insurance against the downside risk.

The scientific contribution of Article 1 consists of its systematic treatment of climate policy in heat and power capacity investment decisions, in particular regarding flexibility.

(2) Emissions trading and investment decisions in the power sector– a case study in Finland

The European Union Emissions Trading Scheme (EU ETS) is the most prominent example of a tradable emission permit system for greenhouse gas emissions. Implications of the EU ETS on the power sector investment broadly has been studied e.g. by Reinaud (2003) and de Leyva and Lekander (2003).

Article 2 considers the impacts of the EU ETS in a more detailed regional setting in Finland paying more attention to flexibility. The impacts of a cap-and-trade system are examined from the perspective of a capital investor. First, a brief review on the general mechanisms through which emissions trading affects size, timing and cashflow of an investment decision is provided. Next, the regional investment environment of power producers in Finland is explored. Third, financial impacts of the EU ETS are examined in a hypothetical single-firm investment problem: a 250 MW_e condensing power plant using either coal or natural gas. An exogenous, stochastic price model[16] is applied in the case study in order to extend the standard discounted cashflow (DCF) analysis to better reflect the value of two real options involved: the option to wait and the option to alter operating scale. The value of options is estimated in a normal risk-adjusted framework through a dynamic DCF analysis. Similarly to Deng and Oren (2003), two stochastic variables are used to estimate the value of the real options: the price of electricity without the EU ETS, and the price of an emission allowance.

The case study shows that a result of a quantitative investment appraisal for a gas-fired power plant highly depends on the assumptions made on emissions trading in a power market similar to that of Finland. The impact mainly depends on the assumed price level of emission allowances and the (potential) allocation of free allowances. However, behaviour of the allowance market (e.g. volatility and correlations to electricity and fuel prices) can have a significant impact on the expected return. The case study further shows that the high uncertainty regarding allocation of free allowances is critical to decisions to switch to natural gas. Renewable and nuclear energy remain unaffected by this particular uncertainty.

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[16] See Ventosa et al. (2005) for a taxonomy on electricity market models.

The scientific contribution of Article 2 is the comprehensive treatment of the impacts of the EU ETS in an investment decision involving real options in the power sector. It has been used as reference material in Rong and Lahdelma (2005).

(3) A case study on risk and return implications of emissions trading in power generation investments

Exposure of different types of power generation technologies to the risks of emissions trading differs. Whereas fossil-fuel-fired technologies are subject to a fuel price risk and emission allowance allocation risk and give real options, renewable energies are often subject to a production volume risk and possess robustness.

Article 3 explores the quantitative implications of the EU ETS on risk and return of investments in three specific technologies: a combined-cycle gas turbine (CCGT), an off-shore wind power farm and an existing hydro power plant with a reservoir. A single-firm exogenous and stochastic price simulation model is used to compare the performance of the technologies with the dynamic DCF analysis similar to that of Article 2. The simulation model of Article 3 can, however, deal with multiple uncertain variables. The perspective is that of a capital investor.

First, literature on risk management in power generation investments is briefly reviewed. It is concluded that risk management is useful for companies, and hedging and portfolio diversification can be applied as risk management tools within an emissions trading scheme. This motivates the model to study the long-term return and the total risk (excluding technical and construction-related risks) involved, which is presented next. Finally, the data applied and the results obtained are presented and discussed.

Article 3 shows that emissions trading increases the expected return of all three power plant technologies. The increase in risk is significant only for the CCGT: emissions trading can almost triple the total risk of the CCGT. Investment in an existing hydro power plant portrays as “high profit, low risk” investment. Such opportunities can obviously be expected to be rare in competitive markets and the prices are likely to adapt. CCGT seem to be “negative-to-low profit, high risk” investments, and off-shore wind power a “negative-to-low profit, low risk” investment. Off-shore wind power is viable only in good wind conditions with subsidies. Opportunities for portfolio diversification with the technologies studied are low.

The scientific contribution of Article 3 is the model to compare long-term expected returns and the related risks taking into account selected real options. The model can be applied to a wide range of technologies and be extended to take into account other real options, such as the option to switch product and/or fuel.

(4) Option value of gasification technology within an emissions trading scheme

Real options are sometimes present *both* in the initial setting before the investment *and* in the setting after the investment. This is the case, for example, in many power plant retrofits, where it is necessary to take into account the *change* in the option value. Article 4 explores the impact of a cap-and-trade emissions trading system, and in particular the EU ETS, on these kinds of investments. A similar methodology to that in Article 3 is applied in two actual case studies focusing on a specific technology.

Solid fuel gasification technologies, such as Integrated Gasification Combined Cycle (IGCC) plants, are promising alternatives for future heat and power generation due to the high generating efficiency and favourable characteristics regarding potential carbon dioxide capture. First commercial applications are expected in oil refineries and coal power condensed power plants. The first case study of Article 4 analyzes an investment in gasification of biomass in an existing coal-fired condensing power plant. The gasification plant would give the plant owner a valuable option to switch between fuels (coal and biomass). The second case study explores the value of an option to use gasification of coal in a new residential CHP plant based on a Combined Cycle Gas Turbine (CCGT). During the construction of the CCGT, there is an opportunity for a preparatory initial investment, which represents a compound option to acquire later on (through a follow-up investment in IGCC) an option to switch fuel repeatedly depending on the market situation.

The results show that a straightforward application of discounted cash flow analysis can lead to biased results in competitive energy markets within an emissions trading scheme, where a number of uncertainties potentially combined with several real options can make quantitative investment appraisals very complex. The IGCC technology does not yet seem competitive in power plant retrofits within the EU ETS. The current investment cost of IGCC technology is too high for viable retrofit investments.

The scientific contribution of Article 4 is the model to estimate profitability and its risk (standard deviation) in power plant retrofits with multiple uncertainties and real options. The second case study estimates the value of a real compound option. The case studies also give insights to the conditions under which IGCC plants might become competitive in real applications.

(5) Absolute or relative baselines for JI/CDM projects in the energy sector?

The concept of “baseline emissions” is essential for a baseline-and-credit type emissions trading system. One problem related to standardisation of baselines for different kinds of investments, including the investments in heat and power capacity, has been whether to give the baseline scenario as an *absolute* (in tCO_2 equivalent) or as a *relative* or *rate-based* (in tCO_2 equivalent per unit of production, e.g. MWh) figure. The topic was brought up as one of the main questions in baseline standardisation, as it was thought it could have wide implications regarding the simplicity of baseline determination and the environmental performance of JI and the CDM (Ellis et al., 2001). In addition, the potential co-existence of both absolute and relative baselines was identified to have important implications on risk management of investments (Janssen, 2001). It was argued that both absolute and relative baselines create problems.

Article 5 contributed to this discussion with an analysis on two project types: a heat and/or power generation project and an energy efficiency project. The criteria used in the analysis were accuracy of the GHG emission reduction, and manageability of a GHG emission balance. Hence, the perspective in Article 5 is that of a regulator.

Article 5 shows that relative baselines are a more accurate instrument for the estimation of emission reductions in JI/CDM projects in the energy sector, without posing significant additional risks to the management of GHG emission balances for large entities, such as states or multinational companies. In comparison to absolute baselines, relative baselines indicate in a more realistic and conservative manner the amount of emission reductions obtained within the energy system, and give more appropriate incentives to project sponsors. The additional risks of relative baselines for the manageability of GHG emission balances are likely to be small, compared to the normal deviation of the domestic/internal GHG emissions. Companies with a critical mass and ability to absorb the risk of an activity deviation have the potential to sell constant reductions to risk-averse organisations with a corresponding risk premium.

The scientific contribution of Article 5 consists of its systematic treatment of this specific design problem in baseline-and-credit trading systems in the energy sector. Since its publication, for example Bygrave and Bosi (2004), IDD (2003), Imai et al. (2005), Langniss and Praetorius (2005), Shipworth (2003) and Spalding-Fecher et al. (2002) have used Article 5 as reference material.

(6) Risk and return of project-based climate change mitigation: a portfolio approach

International emission reduction commitments, such as the Kyoto Protocol, raise the interest to find locations and projects, where such emission reductions can be made at the lowest possible cost. However, looking at the cost alone, one easily ignores the fact that risks of alternatives often differ and should be taken into account in the analysis.

Article 6 presents a framework for evaluating investment risks of project-based climate change mitigation. Two kinds of investments are first separated. In a conventional real investment, where the capital is given as equity or debt, the investor is keen to manage all the risks related to the capital jointly. As shown in Articles 1 to 4 above, such a comprehensive risk assessment involves a large number of critical variables. Article 6 studies a different contractual arrangement, where the owner of the plant could give the right to the emission permits generated in a project to another party, a “GHG investor”.

The risks of a “GHG investor” can be categorised as price risks, cost risks and quantity risks. As price and cost risks are difficult to assess quantitatively, Article 6 focuses on the determinants of quantity risk and identifies environmental/technological, economic and social risk factors for six main project types. A methodology is presented to quantify risk and return of such GHG abatement investments, and illustrated using a sample of projects from the US Voluntary Reporting of Greenhouse Gases (VRGHG) Program.

Since the risk factors differ between project types, it is concluded that diversification of investments is a promising risk reduction strategy. Carbon funds not only serve as vehicles to channelling investments, but also help to reduce investment risks. Project risks are high, but show no clear pattern across project types. Since market risks were not considered, the analysis was likely to understate the risks involved in project-based climate change mitigation. Political risks, such as the continuation of emission targets beyond 2012, affect all projects equally. Therefore, they cannot be diversified through investments in different projects.

The main scientific contribution of Article 6 is the analysis of the envisaged contractual arrangement and the quantity risk. Since its publication, for example, Jensen (2003) and Michaelowa et al. (2004) have used Article 6 as reference material.

5. CONCLUDING REMARKS

This thesis presents six separate articles on the impacts of tradable greenhouse gas emission permits on investments in heat and power generation. The articles contribute, on the one hand, to the research on emissions trading system design, and on the other hand, to the research and practical implications of emissions trading systems on investments in heat and power plants. Articles 1 to 4 take the perspective of a capital investor. Article 1 gives an overview on the impacts of climate policy instruments, such as different emissions trading schemes, on investment in heat and power generation capacity. Articles 2 to 4 present case studies on a specific scheme, namely the European Union Emissions Trading Scheme. The impacts of emissions trading are evaluated with a dynamic discounted cash flow analysis taking into account selected real options involved. Article 3 discusses the implications on investment risk management. Article 5 explores a specific design problem from the perspective of a regulator in a baseline-and-credit scheme. Article 6 considers management of investment risks in baseline-and-credit schemes from the perspective of an exotic capital investor.

The main contribution of the work undertaken is on the applied rather than the theoretical side of the research on this topic. The approach of the work has been prescriptive rather than descriptive. The focus of the work has been on quantitative investment appraisal, rather than on identification of investment alternatives or treatment of their qualitative aspects.

Emission permit markets have been and still are strongly developing, which has marked the research approach and research questions posed on the one hand, and the methods used to seek answers to the research questions on the other hand. For example, all articles of this thesis consider the investment decisions in a risk-adjusted framework due to the incompleteness of input and output markets, and regulatory uncertainty. It is possible that mature permit markets, together with financial innovation in the electricity and fuel markets, bring investment decisions in heat and power generation closer to a complete market setting, where derivative prices can be directly used to value assets -- at least for a medium term. Liquid derivative markets are in common interest, since they facilitate the flow of capital by transferring the financial risk to those who are most capable and willing to bear it. The emergence of such markets can be supported by public policy.

Meanwhile, risk-adjusted methodologies, which take into account the different forms of flexibility provided by investment projects are needed both for individual investment decisions in heat and power generation; and for analyses of the energy systems in aggregate. The starting point of this thesis was that companies are price-takers, which is not always the case. Research on strategic interaction, game theory and agent-based modelling can provide valuable new insights to dynamic effects caused by emissions trading schemes in energy markets.

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