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Abstract

In this article we study the economics of adoption and diffusion of combined-heat-and-power generation (CHP, cogeneration), a process technology that typically allows for fuel savings and CO_2 emission mitigation of between 10-40% (as compared to separate heat and power generation) by making use of waste heat that is otherwise released unused to the environment. Particularly, based on micro-economic theoretical reasoning and in a deterministic set-up, we conceptualize and model the decision-making problem of adopting either some CHP or some heat-only generating steam boiler technology, and also explicitly take into account the impact of differences in technical change and other parameters on the optimal timing to adopt. Besides, we show how the CHP adoption model developed can be extended to an economic model of technological diffusion that can be used for empirical research. We find that the dynamics of technical progress can greatly affect the optimal timing of adoption and hence also the diffusion path of CHP technology.

Keywords: Technology adoption, Diffusion of innovation, Cogeneration, CHP, Technical change, Optimal timing;

JEL Classification Nos.: D24, D81, L11, L21, O33, Q41

1 Introduction

Combined-heat-and-power production (cogeneration, CHP) is an energy conversion technology that exploits waste heat which is otherwise released unused to the environment. Compared to the separate generation of heat and power, it allows for overall energy efficiencies of up to 90% and fuel and CO_2 emission savings in the range of 10-40%, depending on the technology used and the system replaced (Madlener and Schmid, 2003a). Therefore, CHP is considered to be a key technology for a more rational utilization of energy that may contribute to climate change mitigation and a more sustainable energy development (IPCC, 2001). Decisions on CHP investments, however, comprise a multitude of factors that have to be taken into account, some of which are prone to uncertainty. In liberalized markets in particular, risks and uncertainties concerning a number of additional (and mainly market-related) variables become important for the profitability of such systems, which tend to make the decision-making process even more complex and challenging than in non-liberalized markets. Nevertheless, market liberalization also tends to increase the possibilities for distributed CHP generation, as access to the grid is facilitated and market power abuse avenged. Other factors, particularly the heterogeneity of the firms concerned and the net benefits these firms expect to reap from the adoption, lead to varying degrees of delay in the adoption process, i.e. the tracing of a diffusion path over time.

Adoption and diffusion of innovative technologies has attracted the attention of economists at least since the seminal studies by Griliches (1957) on hybrid corn and Mansfield (1961) on process technologies in the manufacturing sector, respectively. However, thorough economic studies on the adoption and diffusion of CHP and on regulatory and pricing issues related to CHP are still quite rare. In what follows, we present a brief overview of work in this field of research, before to our own investigation.

Dobbs (1983), in the context of the U.K. electricity sector, has developed a model for studying peak-load pricing and capacity planning for CHP installations facing different market structures, and for analyzing the pricing implications of different market structures for electricity and heat.

Joskow and Jones (1983) have studied optimal decision making of a representative cost-minimizing industrial firm that wants to invest in CHP technology. They have developed a series of simple to more complicated CHP adoption models aiming to identify the interactions among incremental investment costs, fuel and electricity prices, steam load characteristics, and plant scale, as these variables affect the decision to cogenerate, but also the level of CHP capacity a firm would consider economical to install. In Joskow (1984) the author, by building upon his earlier work, empirically studies the situation for the pulp and paper industry in several states of the U.S.

Anandalingam (1985) has introduced a dynamic partial equilibrium model that includes peak-load pricing and social welfare impacts, and then applied it to selected industries in the U.S. economy. The model is used to study investment and investment policy impacts (investment tax credits) as well as to undertake policy simulations.

In contrast, Zweifel and Beck (1987) have dealt with the pricing behavior of utilities for electricity fed into the grid by cogenerators, studying the Averch-Johnson effect of over-capitalization. In the given context this effect implies that capital invested by independent power producers detracts from the allowable base of rate-of-return regulated utilities. The authors have further addressed regulatory issues raised in the context of the U.S. 1978 Public Utility Regulatory Policies Act (PURPA).

Woo (1988) has also tackled the rate design problem of cogenerated electricity that is fed into the grid. In particular, the author has studied the inefficiency of avoided cost pricing rules for cogenerated power in the context of PURPA, by undertaking a social welfare analysis based on the three components consumer surplus, cogenerator profit, and utility profit.

Fox-Penner (1990) has investigated the implications of PURPA, state-level regulation, and state average fuel and electricity prices on the overall investment in CHP technology by independent power producers, using a probabilistic cost minimizing CHP investment model applied on the state level (due to a lack of firm-level data).

Rose and McDonald (1991) have developed a structural micro-econometric model for analyzing the influence of various economic and engineering variables on the CHP adoption behavior in the U.S. chemical and pulp industries. Their main focus has been on the derived demand for electricity, price of purchased electricity, and marginal cost of self-generation.

Dismukes and Kleit (1999) have focused on the econometric modeling of the determinants of CHP utilization by commercial generators and self-generators in the U.S. (Louisiana) under conditions of electricity market restructuring.

Strachan and Dowlatabadi, in a series of papers, have looked at various aspects related to the adoption of engine-CHP systems in the U.K. (Strachan and Dowlatabadi, 1999ab, 2002; the latter also covers the situation in the Netherlands).

Bonilla, Akisawa and Kashiwagi (2002, 2003) have studied the determinants of CHP adoption in the Japanese manufacturing industry. In their 2002 study, the authors have introduced an econometric model specification for CHP adoption based on time series cross-section (panel) data for Japan in the context of deregulation of the Japanese power market. In contrast, in the 2003 study, the authors have used survey-derived data for descriptive diffusion analysis and some econometric estimations with binary choice model formulations (plant-level data).

Kwon and Yun (2003) have empirically estimated the existence and level of economies of scope for CHP systems in Korea with a non-parametric linear programming method.

Madlener and Schmid (2003) have investigated the adoption and diffusion of engine-CHP systems in Germany. In particular, they have provided a thorough descriptive data analysis, NPV calculations, and micro-econometric hazard rate modeling, based on a comprehensive micro-dataset from 1960-98.

Finally, Wickart and Madlener (2004) have modeled industrial CHP adoption under uncertainty using real options theory. With their dynamic and stochastic theoretical model, the authors have studied the decision between an irreversible investment in a CHP system and the alternative of investing in a conventional heat-only generation system (and obtaining all electricity from the grid). In a numerical example, for illustrating the main insights gained from the theoretical analysis, the model has been applied to stylized data, using realistic cost values.

Table 1 summarizes the literature overview just given and provides some further details.

In this article, based on micro-economic theoretical reasoning and building on the earlier work from ourselves and other work just mentioned, we analyze and model the decision-making problem for the adoption and diffusion of CHP technology in continuous time and a deterministic model set-up. We also explicitly take into account technical change and other parameters influencing the decision-making process and the optimal timing of adoption, respectively. With this scope the paper forms the basis for a second paper, in which we extend the framework introduced in direction of a stochastic model set-up (Wickart and Madlener, 2004), as well as for future empirical work on the subject.

The contribution of this paper to the existing literature is essentially threefold: (1) to model the decision-maker's problem of adopting a CHP system from a lifetime perspective and in continuous time; (2) to study the influence of technical progress on the optimal timing of adoption; and (3) to extend the adoption model in direction of a technology diffusion model that can readily be used for empirical work.

The remainder of this article is organized as follows: Section 2 introduces some general considerations regarding the economics of cogeneration technology. In section 3, we introduce a deterministic micro-economic model of CHP adoption in continuous time. In section 4 we discuss the impact of technical progress, exemplified both for an increase in electrical efficiency and a decrease in specific investment costs, on the optimal timing of adoption. Section 5 illustrates how the adoption model for CHP technology can be extended to a diffusion model that may also be used for empirical work. Section 6 concludes.

Table 1. Summary of the economic CHP literature surveyed

Study	*Scope of research (country)*	*Research focus and method(s) applied*	*Data*	*Model(s) used*	*Main findings, conclusions*
Dobbs (1983)	Generic CHP (U.K.)	Pricing and capacity planning under different market structures; analysis of the pricing implications of different market structures for electricity and heat	-	Theoretical peak-load pricing model	(not made explicit)
Joskow and Jones (1983)	Industrial CHP (U.S.)	Optimal decision-making of a representative industrial firm regarding CHP investment	stylized	Series of cost minimization models, hypothetical example	(1) Energy savings from cogeneration do not necessarily imply economic savings. (2) The economics of CHP are very sensitive to absolute and relative values for fuel and electricity costs. (3) The economics of CHP depends critically on the technical characteristics of the industrial plants where it will be used. (4) Different CHP technologies imply very different amounts of electricity production for any particular level of process steam cogenerated.
Joskow (1984)	Industrial CHP (U.S. pulp and paper industry, selected states)	Optimal decision-making of a representative industrial firm regarding CHP investment	1972, 1977, 1980	Cost minimization model (based on Joskow and Jones, 1983), empirical model application	The theoretical model developed is broadly consistent with actually observed firm behavior in the U.S. pulp and paper industry. Econometric results indicate that the supply of cogenerated power varies directly with the operating cost savings that accrue from cogeneration, and the supply of cogeneration varies directly with electricity prices and inversely with fuel prices.
Anandalingam (1985)	Industrial CHP (U.S., selected branches)	Analysis of investment and investment policy (tax credit) impact, policy simulations	-	Dynamic partial equilibrium model (incl. peak-load pricing and social welfare impact)	Investment in cogeneration is feasible even in the absence of tax credits, and tax credits only marginally increase investment in cogeneration.
Zweifel and Beck (1987)	Commercial CHP (U.S.)	Utilities' pricing behavior for cogenerated electricity fed into the grid, incl. regulatory issues; comparison of pricing under rate of return regulation and social welfare optimization	-	Theoretical make-or-buy decision model for three different load segments	(1) Utilities subject to rate of return regulation are subject to an Averch-Johnson effect of over-capitalization, which is expected to be pronounced in the light of a preference to invest in base-load capacity. (2) Optimal buying prices will be different in a rate of return regulated regime, compared to the social optimum (the higher the allowed rate of return, compared to the market rate, the more likely purchase prices will be too low, with a most pronounced deviation in the peak load segment). (3) There is no single allowable rate of return that would guarantee socially optimal buying prices in all load segments. (4) Load specific discount factors can be applied to the components of the rate-making base that would induce the regulated utility to set socially optimal purchase prices for cogenerated energy. Ceteris paribus, the higher the relative capital intensity in the base load, the more strongly should intermediate and peak load components of the rate-making base be discounted (relative to the base load component).

Woo (1988)	Generic CHP (U.S.)	Analysis of the static social welfare effects under PURPA (taking into account consumer surplus + cogenerator profit + utility profit)	-	Efficient pricing model for cogenerated power; economic analysis of the rate design problem for cogenerated power, incl. the inefficiency of avoided cost pricing rules	(not made explicit)
Fox-Penner (1990)	Generic CHP (U.S., state-level analysis)	Impact of PURPA, state-level regulations, and fuel/electricity prices on total CHP adoption in a state	1985 (49 obs.)	Econometric cost minimizing CHP investment decision models, model for the amount of CHP installed	Interstate regulatory differences have significant and sometimes counter-intuitive impacts on independent power generation. Electricity and fuel prices significantly affect the amount of independent power capacity installed. Regulatory effects dominate the decision to invest or not invest in electric capacity.
Rose and McDonald (1991)	Industrial CHP (U.S. chemical industry and paper industry)	Focus on derived demand for electricity, price of electricity purchased; marginal cost of self-generation	1985	Structural micro-econometric model	Industrial cogeneration is determined by the derived demand for electricity, price for electricity purchased, and marginal cost of self-generation. The buyback rate was found to be relevant only under certain circumstances (e.g. low marginal cost and/or high buyback rate), and that the buyback rate for most firms is unimportant in determining the amount of electricity demanded or self-produced. Policy actions related to industrial CHP should focus on the price of electricity and factors that affect the plant's marginal cost of producing electricity.
Dismukes and Kleit (1999)	Industrial CHP (U.S., Louisiana)	CHP utilization of commercial generators and self-generators and electricity market restructuring	1995 (260 obs.)	Econometric electricity demand model, two discrete choice models (logit, ordered choice)	Increasing electricity demand, increasing industrial output, increasing electricity prices, and decreasing natural gas prices all increase probability of choosing on-site generation; fuel switching abilities, steam boiler capacity and steam temperature all have positive and significant impact on the decision to install on-site CHP
Strachan and Dowlatabadi (1999a)	Engine-CHP (U.K.)	Engineering-economic analysis of cogeneration technology adoption; analysis of barriers and supplier strategies	1992-97 (630 obs.)	NPV model	The majority of engine-CHP units with questionable economic return were installed by inexperienced early suppliers
Strachan and Dowlatabadi (1999b)	Engine-CHP (U.K.)	Economic analysis of decentralized CHP technology adoption	1992-97 (600 obs.)	NPV model (profit-maximizing adopter)	70% of installed engine-CHP units in the U.K. were of questionable economic value to adopters; installations with better returns are more likely to be self-financed
Strachan and Dowlatabadi (2002)	Engine-CHP (Netherlands, U.K.)	Comparative study, focus on win-win partnerships between adopters and utilities, and on supplier strategies in response to institutional change	1985-98	Engineering-economic analysis of CHP adoption	Lower economic size threshold for engine-CHP in the Netherlands than in the U.K. and much larger engine-CHP installations
Bonilla et al. (2002)	Industrial CHP (Japan, 7 industries)	Study of CHP adoption in the manufacturing sector	1985-98 time series cross-sectional panel data (1'500 obs.)	2 econometric models: double-logarithmic CHP capacity addition model; fixed effects CHP adoption model	Medium-sized industrial sites have been more active in new CHP adoption; industries that showed a decline in conventional steam capacity have seen increases in CHP capacity; the fixed effects model indicates increasing returns to scale for CHP plants during the sample period

Bonilla et al. (2003)	Industrial CHP (Japan, manufacturing sector)	Survey-based descriptive CHP diffusion and model-based CHP adoption study	1980-2000 plant-level data	Econometric cross-sectional binary choice models	Probability of CHP adoption increases with on-site power consumption, steam demand, operating hours, and payback period (in decreasing order of relevance). Medium-sized manufacturing companies seem to have a bias to adopt CHP technology. The decision to adopt CHP systems larger than 5 MW is conditioned by power consumption, through the power market, steam demand, on-site power needs, and other factors. Models failed to capture technological substitution between CHP and separate power (and steam) production.
Kwon and Yun (2003)	Generic CHP (Korea, Seoul metropolitan area)	Measurement of economies of scope of CHP	1991-99 (39, 6 and 9)	Non-parametric linear programming model	Significant cost reduction effect through fuel saving.
Madlener and Schmid (2003)	Engine-CHP (Germany)	Descriptive data analysis, Economic and econometric model-based analysis for CHP adoption and diffusion	1960-98 (4'921 obs.)	NPV model, hazard rate models, micro-data for all sectors	Electric capacity, total energy efficiency, and the field of application have a significant influence on the probability of adopting engine-CHP systems. Paradoxically, higher specific investment costs seem to have a relation to earlier adoption. The probability of adoption of CHP systems in buildings seems to be lower than for other applications; the same applies for East Germany, as compared to the other regions of the country.
Madlener and Wickart (this study)	Industrial CHP (generic)	Economic modeling of the optimal adoption and diffusion of CHP technology in a deterministic framework	stylized	Deterministic NPV adoption and diffusion model, application in numerical example	The lower the speed of technical progress, the lower is the optimal time of adoption and the higher is the value of the optimal electrical efficiency of the CHP system. Too early adoption of CHP technology can greatly diminish the net present value of adopting a CHP system.
Wickart and Madlener (2004)	Industrial CHP (generic)	Economic modeling of the optimal adoption and diffusion of CHP technology in a stochastic framework. Analysis of the role of stochastic fuel and electricity prices on the value of investment in CHP technology.	stylized	Stochastic CHP adoption model based on real options theory, application in numerical example	Pure net present value calculations may be misleading in estimating economic CHP potentials and energy market regulation might have an impact on economic CHP potentials by altering price volatilities.

2 The economics of cogeneration – some general considerations

Cogeneration technology is more energy-efficient than the separate production of heat and power. However, this does not necessarily mean that it is the profit-maximizing choice for a particular firm. Indeed, demand for CHP exerted by a profit-maximizing firm, D^{CHP}, likely depends on the following explanatory variables:

$$D^{CHP} = f\left(\underset{+}{p_E}, \underset{-}{p_F}, \underset{+}{b}, \underset{+}{L_H}, \underset{+}{L_E}, \underset{-}{\Delta I}, \underset{+}{O}, \underset{+}{\vartheta}, \underset{+}{S} \right) \tag{1}$$

where p_E and p_F denote the purchase price of electricity and fuel, respectively, b the buy-back rate for electricity fed into the grid, L_H the heat load, L_E the electricity load, ΔI the investment cost difference between CHP and heat-only (e.g. steam boiler) technology, O the annual operating hours, ϑ the process heat temperature/s needed, and S the possibility of fuel switching (a binary yes/no variable). Also given are the signs of the expected impact on the demand for CHP technology.

The firm's decision problem of whether or not to adopt CHP technology can be divided into three distinct sub-problems:

(1) The firm has to determine its energy requirements over time, i.e. its heat and electricity load profiles;

(2) Given the heat and electricity load profiles, and economic considerations, the firm has to choose the optimal design of its energy system (optimal capacity/technology adoption planning);

(3) The firm has to decide on the way the installed energy system is going to be operated in an economically optimized way.

Since our interest here is dedicated to the adoption and diffusion of CHP technology, we take the energy demand of the firm as given and assume that its energy system is operated optimally. In other words, in the following we will restrict our attention to the second sub-problem.

3 A micro-economic model of CHP adoption

In order to simplify the analysis further we only consider two energy conversion technology investment options: on the one hand, the adoption of a conventional steam boiler (SB) and, on the other hand, the adoption of a combined-heat-and-power (CHP) system.

3.1 Steam boiler

We assume that the heat demand has to be satisfied at any time *t* (i.e. we rule out any possibilities to buy heat energy from external suppliers). For expositional simplicity we further assume that the boiler can be infinitely used (i.e. there is no technical depreciation) and that the fuel costs are the only operating costs that occur.[1] Then the lifetime operating costs of a steam boiler installed at time *t* can be specified as:

$$C_F^{SB}(t)=\int_t^{\infty} p_F(\tau)\frac{L_H(\tau)}{\eta^{SB}(t)}e^{-r(\tau-t)}d\tau \tag{2}$$

where p_F denotes the fuel price, L_H the heat load profile, η^{SB} the thermal efficiency of the steam boiler (which is subject to technical progress over time t ; see also section 4 below), and r the discount rate applied. If only a steam boiler is being installed, no self-generation of electricity takes place, and all electricity needed, represented by the electricity load L_E, has to be purchased via the grid. Hence for the case of adopting a steam boiler the lifetime costs of electricity purchased at price, p_E, are:

$$C_E^{SB}(t)=\int_t^{\infty} p_E(\tau)L_E(\tau)e^{-r(\tau-t)}d\tau \tag{3}$$

3.2 CHP system

The lifetime operating costs of a CHP system installed at time *t* can be specified in an analogous manner. With respect to operating (fuel) costs, one gets:

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[1] Fuel costs typically dominate operating costs. Note that neglecting other operating costs and maintenance costs implies that our model will tend to overestimate the profitability of the investment considered. The inclusion of operating costs other than those for fuel input and of maintenance costs is straightforward and does not alter the major conclusions that can be made.

$$C_F^{CHP}(t)=\int_t^{\infty} p_F(\tau)\frac{L_H(\tau)}{\eta_H^{CHP}(t)}e^{-r(\tau-t)}d\tau \tag{4}$$

where η_H^{CHP} denotes the thermal efficiency of the CHP system.

The lifetime costs of electricity in the case of CHP technology adoption depend on the level (and timing) of self-generation and the actual demand for electricity. If actual demand exceeds self-generation, electricity has to be bought from the grid. For expositional simplicity we assume that the electricity price is independent of whether or not the firm operates a CHP system.[2] Conversely, self-generated excess electricity can be sold to the grid at the buy-back rate b offered by the local electric utility company. Hence we may specify

$$C_E^{CHP}(t)=\int_t^{\infty}\left\{p_E(\tau)\max\left[L_E(\tau)-\frac{L_H(\tau)}{\eta_H^{CHP}(t)}\eta_E^{CHP}(t),0\right]-b(\tau)\max\left[\frac{L_H(\tau)}{\eta_H^{CHP}(t)}\eta_E^{CHP}(t)-L_E(\tau),0\right]\right\}e^{-r(\tau-t)}d\tau \tag{5}$$

where η_E^{CHP} denotes the electrical efficiency of the CHP system considered.

3.3 The decision-making problem

Since generally $\eta^{SB}>\eta_H^{CHP}$ it follows, for a given heat demand, that $C_F^{SB}<C_F^{CHP}$, while for a given electricity demand, it follows that $C_E^{SB}>C_E^{CHP}$. However, not only the lifetime operating (fuel) costs and electricity costs differ, but also the (heat) specific investment costs, $I_S^{SB}(L_{H,\max},t)$ and $I_S^{CHP}(L_{H,\max},t)$. The time argument t represents technical progress, i.e. the decrease in specific investment costs over time, and $L_{H,\max}$ the thermal capacity of the heat generation system, which is assumed to be constant. Total investment costs can then be written as:

$$I^i(t)=L_{H,\max}\cdot I_S^i(t) \tag{6}$$

The cost reductions achievable from adopting a CHP system, as compared to a steam boiler system, can be defined by the saved lifetime expenses for electricity less the additional lifetime fuel costs that accrue from cogeneration, i.e.

[2] In practice utilities may have incentives to discourage independent CHP production and thus may or may not be willing to offer buy-back rates to (potential) cogenerators that make CHP operation sufficiently attractive for them to start/continue cogeneration (see Anandalingam, 1985, and Zweifel and Beck, 1987, among others).

$$\Delta C(t) \equiv \left[C_E^{SB}(t) - C_E^{CHP}(t)\right] - \left[C_F^{CHP}(t) - C_F^{SB}(t)\right]. \tag{7}$$

On the other hand, the investment costs of a CHP system are higher than those of a steam boiler. If we denote the maximum heat load as $L_{H,\max}$, then the additional investment costs are defined as:

$$\Delta I(t) \equiv L_{H,\max}\left[I_S^{CHP}(t) - I_S^{SB}(t)\right] \tag{8}$$

The decision to adopt CHP rather than SB technology is associated with the value *V*, given by the difference between cost reductions and additional investment costs:

$$V(t) \equiv \Delta C(t) - \Delta I(t) \tag{9}$$

Note that for providing an economic incentive to adopt CHP technology, *V* has to be strictly positive. Now we can specify the net present value of adopting a CHP system instead of a conventional steam boiler system at time $t = 0$ as:

$$J\left[V(t)\right] = V(t)e^{-rt} = \left[\Delta C(t) - \Delta I(t)\right]e^{-rt} \tag{10}$$

A rational, risk-neutral firm with perfect foresight will invest in a CHP plant if the difference between reduced energy costs and additional investment costs, both expressed in net present values at the time of adoption *t*, is maximized.

In the analysis it provides useful to distinguish between economic and technical variables influencing the economics of CHP technology adoption and diffusion. Here, we restrict ourselves to present some basic mechanisms on how fuel and electricity prices affect the economic viability of CHP technology, followed by a detailed analysis of the role of technical progress on the optimal timing of adoption.

From studying the impacts of fuel and electricity prices on the operating costs we can come up with the following stylized facts for the main economic variables affecting the adoption of CHP technology:

- *Fuel price:* In the case of CHP, electricity is produced by using (predominantly) fossil-based fuels. Therefore, if fuel prices increase the marginal costs of providing heat for matching the heat load, L_H, are likely to increase more in case of cogeneration than if all electricity is bought from the grid and, hence, *ceteris paribus*, the operating cost difference between steam boiler and CHP generation decreases.

- *Electricity price:* In the absence of CHP all electricity must be bought from the grid. Consequently, the costs for electricity increase with rising electricity prices and thus the operating cost difference between owning a steam boiler and a CHP system increases as well.

- *Buy-back rate:* In the case of CHP and sufficient self-generation the total revenue of electricity delivered to the grid increases as the buy-back rate increases and hence also the cost difference.

Apart from these main economic variables technical progress plays a crucial role for the optimal timing of adoption, an issue to which we turn next.

4 Optimal timing of adoption and the role of technical progress

The process of technical progress is a complex phenomenon that is characterized, for example, by cumulative learning, economies of scale, and spillover effects. The speed and direction of technical progress depends on industry and market structures, and on policies that influence the incentives to invent, innovate, or adopt new products, production processes, intermediate inputs, management methods etc. (e.g. Mansfield, 1968; Stoneman, 1995; among others). Technical progress has an impact on the economics of CHP mainly through two channels: On the one hand, the energy efficiency of the CHP system increases over time while, on the other hand, specific investment costs decrease.

4.1 Optimal time of adoption

Hence, the unknown optimal time t^* of adoption (Dixit and Pindyck, 1994, p.138) is given by the following first and second order conditions, Eqs. (11) and (12), as well as by the adoption condition, Eq. (13):

$$r = \frac{\dot{V}\left(t^*\right)}{V\left(t^*\right)}, \tag{11}$$

$$r \geq \frac{\ddot{V}\left(t^*\right)}{\dot{V}\left(t^*\right)} \tag{12}$$

and

$$J\left[V\left(t^*\right)\right] > 0 \;\Rightarrow\; V\left(t^*\right) > 0 \;\Rightarrow\; \dot{V}\left(t^*\right) > 0, \tag{13}$$

The first order condition for an optimum, Eq. (11), implies that the rate of change in the value to adopt, *V*, has to be equal to the discount rate *r*. The second order condition, Eq. (12), can be interpreted as a compound interest effect: At the optimal investment time the discount effect has to be stronger than the growth rate of the change in the value to adopt. Otherwise, it would be more optimal to wait since the net present (i.e. discounted) value to adopt, $J[V(t)]$, still increases (see Eq. (15)).

In order to analyze the role of technical progress for the economics of CHP adoption we assume constant energy prices and demand, and that the amount of self-generation of the firm concerned is always lower than its electricity demand. The cost reduction function (Eq. (7)) can then be re-written in terms of heat specific costs as:

$$\Delta c\left(t\right) \equiv \frac{\Delta C\left(t\right)}{L_H} = \frac{1}{r}\left(p_E \frac{\eta_E^{CHP}\left(t\right)}{\eta_H^{CHP}\left(t\right)} - \frac{p_F}{\eta_H^{CHP}\left(t\right)} \frac{\eta^{SB}\left(t\right) - \eta_H^{CHP}\left(t\right)}{\eta^{SB}\left(t\right)} \right) \tag{14}$$

$\Delta c(t)$ represents the cost reduction that can be achieved with a cogeneration system compared to a steam boiler per unit of heat produced, whereas the first term between the brackets in Eq. (14) stands for the electricity saved per unit of heat produced. The second term represents the additional fuel costs incurred for producing one unit of heat when using a CHP system instead of a steam boiler. Hence, the cost reductions are positive if the saved electricity expenses per unit of heat produced exceed the additional fuel costs to produce one unit of heat in a cogeneration system, compared to the conventional system. The additional investment costs can also be expressed as heat-specific costs:

$$\Delta i\left(t\right) \equiv \frac{\Delta I\left(t\right)}{L_H} = I_S^{CHP}\left(t\right) - I_S^{SB}\left(t\right) \tag{15}$$

where $\Delta i(t)$ indicates the heat-specific additional investment costs for co-generation.

In order to analyze the optimal time of adoption as a function of technical progress, we need to know the first derivatives of the heat-specific cost reduction function Eq. (14) and the additional investment cost function Eq. (8):

$$\Delta\dot{c}(t) = \frac{1}{r}\left[p_E \frac{\eta_E^{CHP}(t)}{\eta_H^{CHP}(t)} \hat{\eta}_E^{CHP}(t) - \left(p_E \frac{\eta_E^{CHP}(t)}{\eta_H^{CHP}(t)} - \frac{p_F}{\eta_H^{CHP}(t)} \right) \hat{\eta}_H^{CHP}(t) - \frac{p_F}{\eta^{SB}(t)} \hat{\eta}^{SB}(t) \right] \tag{16}$$

$$\Delta\dot{i}(t) = \dot{I}_S^{CHP}(t) - \dot{I}_S^{SB}(t) \tag{17}$$

Further, we also define the value to adopt in terms of heat unit costs:

$$v(t) \equiv \frac{V(t)}{L_H} = \frac{\Delta C(t) - \Delta I(t)}{L_H} = \Delta c(t) - \Delta i(t) \tag{18}$$

At the optimal time of adoption we have:

$$r = \frac{\dot{v}(t^*)}{v(t^*)} \equiv \hat{v}(t^*), \quad r \geq \frac{\ddot{v}(t^*)}{\dot{v}(t^*)} \equiv \hat{\dot{v}}(t^*), \quad J\left[v(t^*)\right] > 0 \tag{19}$$

Now we can identify the impact of technical progress on the specific value of adoption: An increase in the electrical efficiency raises the value of adoption, since saved electricity expenses increase. The impact of a change in the thermal efficiency of cogeneration is ambiguous: On the one hand, saved electricity expenses decrease, because a smaller scale cogeneration plant can be installed to meet the heat load demand. On the other hand, fuel costs of cogeneration also decrease. The impact of the cost reductions depends on which of these two effects dominates. Further, if the thermal efficiency increases, the total investment cost difference decreases even though specific investment costs increase. In contrast, if the thermal efficiency of the steam boiler is enhanced, total cost reductions decrease since the fuel cost difference increases. Additionally, the total investment cost difference increases as well.

4.2 The role of technical progress

In this section we analytically analyze the effect of technical progress on the optimal time of adoption. Here, technical progress enters through two different channels:

(1) A change in the energy efficiency of cogeneration as well as of conventional heat generation technology, and

(2) A decrease in investment costs.

In the previous section, we have analyzed the impact of an improvement in the electrical efficiency of cogeneration. Now, if in Eq. (14) only η_E^{CHP} changes with time, we can derive the first and second order conditions in terms of η_E^{CHP}:

$$\frac{\frac{p_E}{r}\frac{\eta_E^{CHP}\left(t^*\right)}{\eta_H^{CHP}}}{v\left(t^*\right)}\hat{\eta}_E^{CHP}\left(t^*\right)=r \quad \text{and} \qquad \hat{\hat{\eta}}_E^{CHP}\left(t^*\right)\leq r \tag{20}$$

Due to the adoption condition, the denominator of the first order condition has to be positive. At the optimal time of adoption, the rate of change in the electrical efficiency weighted by the share of saved electricity expenses in the total specific value of adoption must equal the discount rate, *r*. We see a maximum if the rate of change in the electrical efficiency, $\hat{\hat{\eta}}_E^{CHP}$, falls below the discount rate.

If the thermal efficiency of the steam boiler improves (i.e. $\hat{\eta}^{SB}$ is positive), then one would expect that the value of adoption will be ever decreasing. Inspecting the first order condition (Eq. 21) we see that the left hand side is negative for positive $\hat{\eta}^{SB}$, since the share of the fuel costs of a steam boiler in the specific value of adoption is always negative.

$$-\frac{\frac{1}{r}\frac{p_F}{\eta^{SB}\left(t^*\right)}}{v\left(t^*\right)}\hat{\eta}^{SB}\left(t^*\right)=r \tag{21}$$

Hence, we can see that Eq. (21) only holds if the heat-specific value of adoption is negative, which violates the adoption condition.

A change in the thermal efficiency of cogeneration has an ambiguous effect. On the one hand, the fuel costs and marginal capital costs change while, on the other hand, if the electrical efficiency is held constant, the amount of electricity cogenerated per heat unit changes and, therefore, also the electricity costs saved. Proceeding in the same manner as before yields:

$$\frac{\frac{1}{r}\left(\frac{p_F}{\eta_H^{CHP}\left(t^*\right)} - p_E \frac{\eta_E^{CHP}}{\eta_H^{CHP}\left(t^*\right)}\right)}{v\left(t^*\right)} \hat{\eta}_H^{CHP}\left(t^*\right) = r \tag{22}$$

At the optimal time of adoption, the rate of change in the thermal efficiency of the cogeneration system, weighted by the share of net cost reductions on the specific value of adoption, has to be equal to the discount rate. If the thermal efficiency of the cogeneration system increases, fuel costs decrease. However, saved electricity costs decrease as well, since a smaller cogeneration plant is needed to meet the given heat demand.

Usually, technical progress in cogeneration increases total efficiency and electrical efficiency, whereas the thermal efficiency of the cogeneration system falls. In this case $\hat{\eta}_H^{CHP}$ is negative. If the electrical and the thermal efficiency of the cogeneration system changes, the first order condition becomes:

$$\frac{\frac{1}{r}\left(p_E \frac{\eta_E^{CHP}\left(t^*\right)}{\eta_H^{CHP}\left(t^*\right)} \hat{s}^{CHP}\left(t^*\right) + \frac{p_F}{\eta_H^{CHP}\left(t^*\right)} \hat{\eta}_H^{CHP}\left(t^*\right)\right)}{v\left(t^*\right)} = r \tag{23}$$

where $\hat{s}^{CHP}$ denotes the relative change in the electricity rate of the cogeneration system. For an interior solution, the additionally saved electricity costs per heat unit due to an increase in the electricity rate have to outweigh the additional fuel costs due to the falling thermal efficiency.

A similar analysis can also be made for decreasing investment costs. The difference in the rate of change between the specific investment costs for the steam boiler and co-generation technology, weighted by its share in the specific value to adopt, must equal the discount rate.

$$\frac{I_S^{SB}\left(t^*\right)}{v\left(t^*\right)} \hat{I}_S^{SB}\left(t^*\right) - \frac{I_S^{CHP}\left(t^*\right)}{v\left(t^*\right)} \hat{I}_S^{CHP}\left(t^*\right) = r \tag{24}$$

The above analysis also shows the *importance of expectations* in the context of technology diffusion (Rosenberg, 1976; Ireland and Stoneman, 1986) with respect to two important technical parameters: electrical efficiency increases and (specific) investment cost decreases. Obviously, a broader analysis would have to incorporate all economic and technical parameters and variables considered important. Moreover, in order to explicitly include uncertainty in the analysis, this would call for the development of a stochastic CHP adoption model, like the one introduced in Wickart, Madlener and Jakob (2004).[3] In such a stochastic model it would also be possible, for example, to consider unforeseen changes in heat demand caused by *radical technological innovation* (such as the switching from thermal to biochemical processes in the chemical industry).

5 A cogeneration diffusion model

5.1 General considerations

In contrast to investigations into technology adoption, where typically drivers for adoption at one point in time are studied, technology diffusion studies focus on "the process by which new technologies spread across their potential markets over time" (Stoneman, 2001, p.3). As a matter of fact, *invention* and *innovation* have attracted much more interest in the past, although it is ultimately the diffusion process that creates economic welfare.

In diffusion research, it is acknowledged that technology diffusion can be a (more or less) time-intensive process. Furthermore, it is taken into consideration that firms are heterogeneous, and that diffusion may thus differ across and within firms and industries (inter- and intra-firm and inter- and intra-industry diffusion), but also across and within regions or countries.

In the literature on the economics of technological diffusion, a useful distinction has been made between rank, stock, order and epidemic effects determining the diffusion path (Karshenas and Stoneman, 1993). In what follows we will first explain the different character of these four effects, which are not yet common in the energy economics literature, and then provide a short outline of a theoretical diffusion model specification for CHP systems.

Rank effects result from the assumption that potential adopters have different inherent characteristics and, therefore, obtain different benefits from the use of a new technology, which in turn determine the individually preferred adoption dates. Rank models, typically specified as probit models, are operationalized by decreasing merit order rankings. This means that firms

[3] In the EU-funded research project 'OSCOGEN' (Contract No. ENK5-2000-00094; duration 11/2000-1/2003), for instance, a stochastic model has been developed for the *optimal operation* of CHP systems in a liberalized market environment (cf. Madlener and Weber, 2004, forthcoming).

are ranked according to their (expected) benefit from adoption, generating a benefit distribution across these potential adopters. With the help of an acquisition rule that compares benefits to costs of adoption, it is possible to derive a distribution of reservation acquisition costs from the benefit distribution. When acquisition costs are assumed to fall over time (e.g. due to economies of scale and learning effects), more and more adopters will find it attractive to adopt the technology as time goes by.

Stock effects reflect the assumption that the benefit from adoption accruing to the marginal adopter decreases as the number of earlier adopters rises. Stock models (often labeled 'game-theoretic' because of the explicit consideration of strategic interactions) are operationalized by arguing that for any given cost of technology acquisition there will be a number of adopters beyond which adoption is not profitable (the number of adopters which is assumed to actually adopt at that cost of acquisition). In case of decreasing acquisition costs, further adoptions can be assumed to take place, generating a diffusion path. The impact of earlier adoptions on the benefit of the marginal adopter results from endogenizing the output decisions of firms in the model. Firm output changes (affecting industry output) will affect industry prices and thus the profitability of further adoption.

Order effects accrue from the assumption that returns to a firm from adopting a new technology depend upon the firm's position in the order of adoption (greater returns are achieved by high-order adopters, lower returns by low-order adopters). Order models are operationalized by arguing that the adoption decision by a firm incorporates the effect of how waiting with adoption will affect the firm's profits. For given technology acquisition costs, it will only be profitable to adopt a technology down to a certain point in the order of adoption. As acquisition costs are assumed to decrease over time, the number of adopters increases over time, mapping out the diffusion path.

Epidemic effects result from the assumption that technologies spread like infectious diseases among a certain population of potential adopters. In its simplest form, epidemic models assume that a potential adopter becomes an adopter just by having contact with an earlier adopter. The larger the number of adopters the greater is the probability that a potential adopter meets an earlier adopter and becomes an adopter herself. Over time, however, the number of individuals that have not yet adopted the technology will decrease, generating an S-shaped diffusion curve.

5.2 A micro-economic model of CHP diffusion

Our starting point for the formulation of a diffusion model, that explicitly incorporates heterogeneity in the benefits that accrue to different firms from adopting a technology, is the specification introduced by Stoneman and Kwon (1996) in the context of four technologies: computer numerically controlled (CNC) machine tools, coated carbide tools, microprocessors for process operations, and computers for administrative operations.

Assume that the gross profit at time τ from adopting a new CHP technology by firm i in time t can be expressed by the following function:

$$g_i(t,\tau) = g\left(\mathbf{C}_i(\tau), N(t), K(\tau)\right), \quad \tau \geq t, \tag{25}$$

with $g_N < 0$ and $g_K < 0$, the first derivatives with respect to the second and third argument, respectively. $\mathbf{C}_i$ is a vector-matrix of firm- and industry-specific characteristics that represent the rank effects, and N and K stand for the number of firms that have already adopted the technology in time t (representing the order and stock effects, respectively).

From that we can write the present value of the increase in gross profits that arises from the adoption of the CHP technology at time t, G_i, as

$$G_i(t) = \int_t^{\infty} g\left(\mathbf{C}_i(\tau), N(t), K(\tau)\right) e^{-r(\tau-t)} d\tau \tag{26}$$

Two conditions must be fulfilled, a *profitability condition* and an *arbitrage condition*. The first one, Eq. (27), implies that the adoption of the technology must yield some positive profit, measured as the net present value NPV_i of adoption, and computed as the difference between G_i and the cost of acquiring the CHP technology, P. The second condition, Eq. (28), requires that the net benefit from adoption is not increasing over time, as otherwise it would be rational to wait with the adoption.

$$NPV_i(t) = G_i(t) - P(t) \geq 0 \tag{27}$$

$$\frac{d\left(NPV_i(t)e^{-rt}\right)}{dt} \leq 0 . \tag{28}$$

The optimal time to invest in a CHP technology, t^*, is determined by the second condition, while the first condition determines the set of potential adopters.

In our case the vector-matrix $\mathbf{C}_i$ may contain a list of firm-specific and industry-specific variables, as depicted in Eq. (1), but in addition also comprise technological variables that characterize both the CHP system envisaged as well as competing technologies. Note also that the adoption model introduced above fits nicely into this specification, in that we can straightforwardly use the formulation of the net present value given in Eq. (10) to cover the rank effects of diffusion ($\mathbf{C}_i$), and extend it to additionally incorporate stock, order, and epidemic effects.

5.3 Applying the theoretical diffusion model

In this section we demonstrate how our theoretical model could be transformed into a workable empirical model specification for the diffusion of CHP systems. In so doing, we first discuss what concrete manifestations the different diffusion effects distinguished in theory (i.e. rank, stock, order, and epidemic effects) may have for the case of CHP technology adoption, followed by a mathematical formulation of an estimable diffusion model specification.

Rank effects cover the fact that the benefit of adopting a technology may differ among firms (or industries). Concerning industrial CHP systems, important variables affecting the profitability of CHP use include the electricity price and the buy-back rate obtained, fuel prices, demand for heat and electricity (overall level and load profiles), annual operating hours (which may differ greatly among different industry branches, as has been shown e.g. in Madlener and Wickart, 2003, for the Swiss pulp and paper and the chemical industry), process heat temperature etc.

Stock effects address changes in the benefits from adoption to the marginal adopters that arise from the number of earlier adoptions. In an industry context, structural changes play a particularly important role. In recent years, for example, a significant concentration process has taken place in the pulp and paper industry, which also involved significant technological change.

Order effects, in contrast, target the relative merits of technology adoption as a function of the firm's position in the order of adoption. First-mover advantages fall into this category, but also acquisition cost decreases due to (expected) technical progress related to CHP systems, and learning and spillover effects, that make waiting to adopt more attractive.

Finally, *epidemic effects* deal with the (possible) intensity of interaction with earlier adopters as an explanatory variable for the diffusion process. For obvious reasons, this intensity can be expected to strongly depend on the ratio between previous adopters and potential adopters (i.e. the point on the – typically S-shaped – diffusion curve). Applied to industrial CHP utilization, this effect can be expected to be more relevant in cases where an open climate and intensive communication prevails among the different actors involved (e.g. technical managers may exchange ideas and experiences on a regular basis at round tables; changes in the energy supply system are documented in detail and made available to others). Additionally, information deficiencies leading to a difference between the optimal and the actual time of adoption might be interpreted as an epidemic effect.

In what follows, based on Stoneman and Kwon (1996), we derive an estimable model equation that allows for the evaluation of the impact of CHP adoption on the firm profitability, taking into account possible rank, stock, order, and epidemic effects.

The gross profits of a firm i at time τ, π_i, contemplating the adoption of some CHP technology, is defined as:

$$\pi_i(\tau) = \pi_{i0}(\tau) + D_i g_i(t_i, \tau) \tag{29}$$

where π_{i0} denotes the counterfactual profits for the case that the CHP technology has not been adopted, D_i a dummy variable that is equal to unity if the firm has adopted CHP and zero otherwise, and $g_i(t_i, \tau)$ denotes the annual gross profit at τ from adopting the technology at t_i (see also Eq. 25).

At the time of adoption the annual gross profit from adoption must equalize the annualized acquisition cost, corrected by its expected change, by the expected cost effects due to changes in the number of adopters at time t_i (order effect), and by a term that describes the profit impact of a divergence between the optimal and the actual timing of adoption, given the information available to the firm (epidemic effect,). Hence we can write

$$g_i(t_i, t_i) = rP(t_i) - p(t_i) + \frac{g_N n(t_i)}{r} + \Phi(t_i - T) \tag{30}$$

The annualized costs of the technology, rP are defined by the interest rate r and the cost of acquiring the technology, P. These costs have to be corrected by the expected change in the acquisition cost (i.e. supply-side effects – e.g. caused by economies of scale and learning-by-doing, or by changes in market structure and competition), p, and the profit impact due to the anticipated order effect caused by a change in the number of other adopters, n. Epidemic effects are captured by the last term, $\Phi(t_i - T)$. T denotes the first appearance of the technology in the market, $\Phi > 0$ indicates that the adoption was too early, and $\Phi < 0$ that it was too late.

In order to obtain a workable expression for $g_i(t_i, \tau)$ we use a first order Taylor series expansion and add a term to capture demand-side effects (e.g. due to learning-by-using or scale effects on the adopter's side), $\beta(\tau - t_i)$, which so far have not been considered:

$$g_i(t_i,\tau) = g_i(t_i,t_i) + \frac{\partial g_i(t_i,\tau)}{\partial \tau}(t_i - \tau) + \beta(\tau - t_i) \tag{31}$$

Using Eqs. (29) to (31), the gross profits of the firm can now be written as:

$$\pi_i(\tau) = \pi_{i0}\left[C_i(\tau), K(\tau)\right] + D_i\left[rP(t_i) - p(t_i) + \frac{g_N n(t_i)}{r} + \Phi(t_i - T) + \frac{\partial g_i(t_i,\tau)}{\partial \tau}(t_i - \tau) + \beta(\tau - t_i)\right] \tag{32}$$

Commonly, for empirical convenience, it is assumed that the function $g_i(t_i, \tau)$ is linear in its arguments, in order to yield a simplified formulation of the term $(\partial g_i / \partial \tau)(t_i - \tau)$ and, consequently, an estimable equation. Note that the counterfactual profits are dependent on firm- and industry-specific characteristics as well as the number of adopters (a growing number of adopters is expected to impact the profits of non-adopters negatively).

Inspection of Eq. (33), which describes the dynamics of the gross profits of a specific firm over time, and the result of our theoretical analysis made in section 3, reveal some interesting insights into the process of technical progress. First, technical progress changes the cost of acquiring the technology (e.g. decreasing specific investment costs) or raise the annual gross profit if the firm adopts the technology. But there also exists a gain from postponing the investment, since in the case of later adoption the annual gross profit might increase due to decreasing operating costs. Apart from these effects, technical change may also change the coefficients of the stock and order effects. In case of technical progress in cogeneration, the decrease in energy costs might affect product prices in energy intensive industries. Even the pure existence of more cost efficient new technologies might be used by large industrial customers as a threat in price negotiations with electricity suppliers in order to obtain more favorable terms and conditions. Hence, if the output market is competitive, cost reductions would drive down product prices, which affects the value of adoption for all firms within an industry (stock effect). Besides, technical progress might also affect the position of a firm within the order of adoption. If technical progress in cogeneration mainly affects electrical efficiency, then for firms with a high electricity load profile and a low heat load profile adoption might become more attractive than for firms with a high head load demand.

6 Summary and conclusions

In this paper we have discussed the economic modeling of cogeneration versus steam boiler technology adoption and diffusion in a deterministic framework. Starting from a net present value optimization criterion for technology adoption, we have shown how technical progress influences the optimal timing of adoption. From there, we have expanded the adoption model into a diffusion model that allows to explicitly model the technology diffusion process over time. This process is driven, on the one hand, by techno-economic characteristics of the adopting firm itself and, on the other hand, by the adoption behavior of competing firms. In a numerical example we have shown that the lower the speed of technical progress, the lower is the optimal time of adoption and the higher is the value of the optimal electrical efficiency of the CHP system. We have further shown that too early adoption of CHP technology can greatly diminish the net present value of adopting a CHP system. The paper has laid the foundation both for empirical work and the stochastic modeling of CHP adoption and diffusion within a new investment (real option) theory framework.

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Appendix: Numerical example

In this appendix we illustrate the theoretical insights gained from our adoption model in a numerical example. In particular, we determine the impact of technical progress on the optimal time of adoption. To calibrate the model, we use the following parameter values:

Table 2. Parameterization of the numerical example

Parameter	Symbol	Value	Unit
Heat load	L_H	13	MW
Electricity load	L_E	6	MW
Operation time		8'760	h/a
Discount rate	r	5%	p.a.
Fossil fuel price	p_F	30	€/MWh
Electricity price	p_E	60	€/MWh
Thermal efficiency of steam boiler	η^{SB}	0.9	
Thermal efficiency of cogeneration	η_H^{CHP}	0.6	
Electrical efficiency of cogeneration	η_E^{CHP}	0.2	
Total investment costs of steam boiler	I^{SB}	1.65	mio. €
Total investment costs of cogeneration	I^{CHP}	4.60	mio. €

We assume that the increase in the electrical efficiency of the cogeneration system follows a logistic function of the form:

$$\eta_E^{CHP}(t) = \underline{\eta}_E^{CHP} + \frac{\overline{\eta}_E^{CHP} - \underline{\eta}_E^{CHP}}{1 + e^{-\alpha(t-\beta)}} \tag{33}$$

where $\underline{\eta}_E^{CHP}$ stands for the electrical efficiency of the first cogeneration system, $\overline{\eta}_E^{CHP}$ indicates the maximum achievable electrical efficiency, and α and β are parameters to be determined. For the speed of the technical progress, α, we choose values between 0.1 and 1. Parameter β has been calibrated such that $\eta_E^{CHP}(0) = 0.151$. Figure 1 shows some paths of the increase in the electrical efficiency of cogeneration as a function of the timing to adopt and for different values of α. It can be seen that the more slowly technical change progresses, the longer a potential CHP technology adopter should wait to invest.

Figure 1. Alternative paths of technical progress

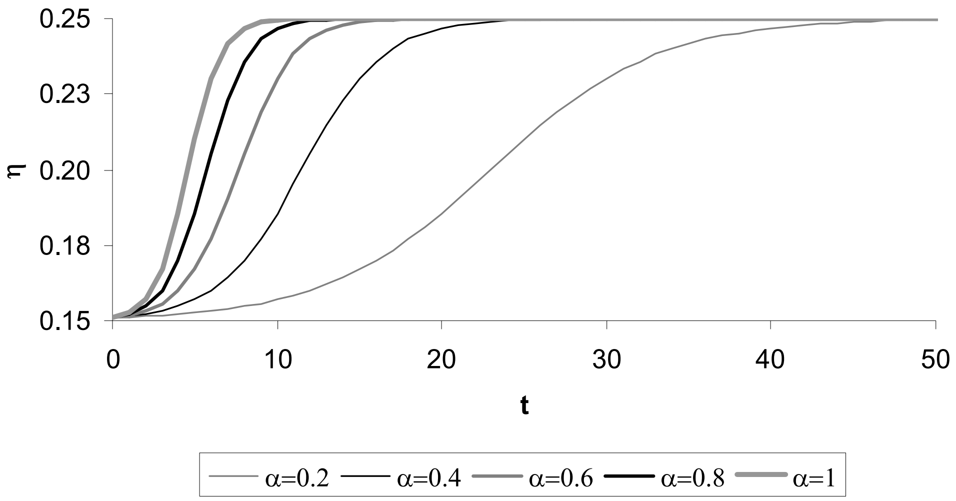
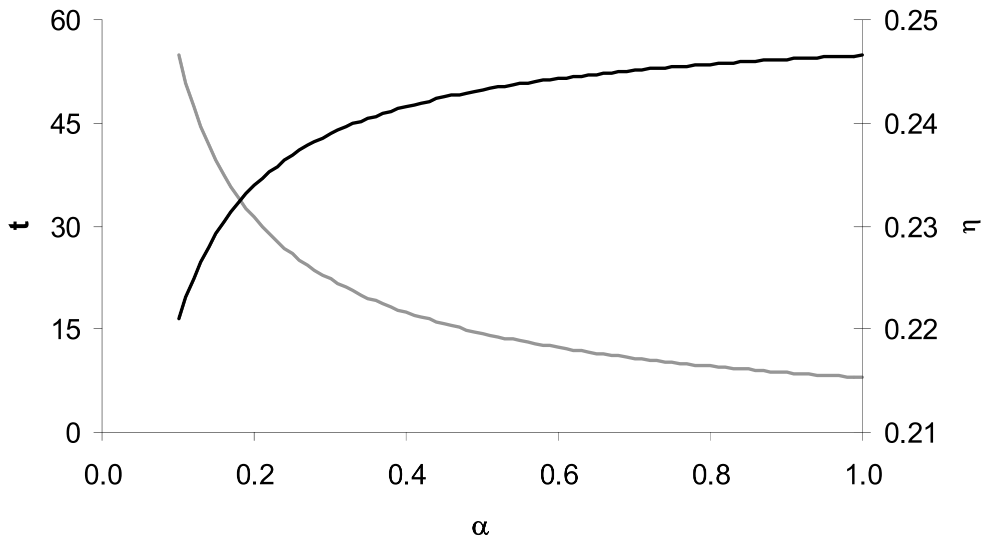


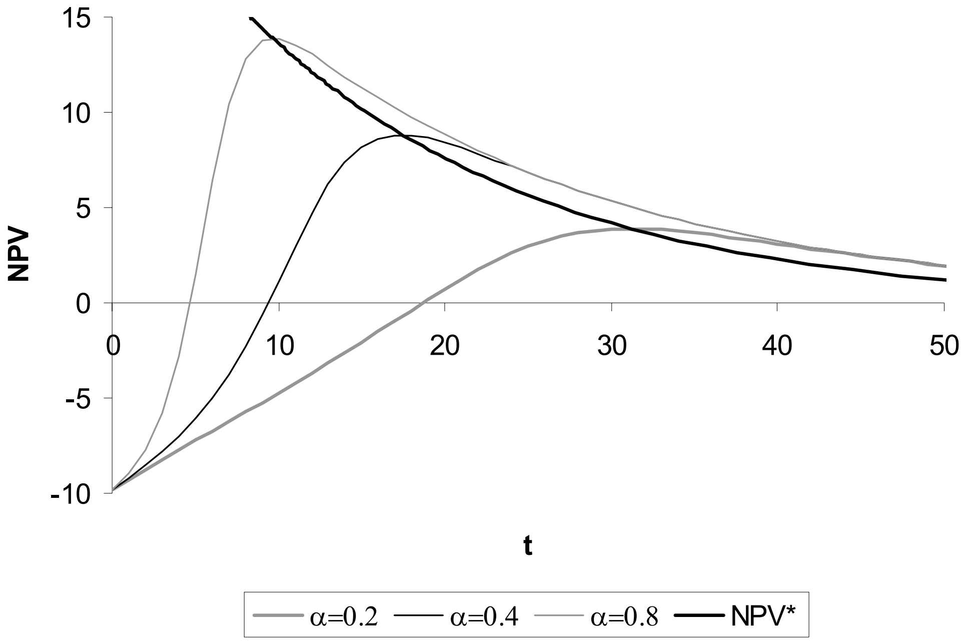
Figure 2 shows that with increasing speed of technical progress α the optimal time of adoption (i.e. optimal duration of waiting to invest into CHP technology) decreases and the optimal (i.e. maximum achievable) electrical efficiency increases. Both effects increase the optimal net present value of adoption: the higher the electrical efficiency, the higher is the value of adoption, and the shorter the optimal time of adoption, the lesser is the discounting effect.

Figure 2. Optimal time of adoption and optimal electrical efficiency



The sensitivity of the net present value to changes in α can be seen from Figure 3, where we have plotted the development of the net present value for different technical progress rates (towards an optimal value *NPV**) against the time of adoption, *t*.

Figure 3. Development of net present value of adoption for alternative technical progress rates and optimal net present value of adoption



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