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Environmental policy and technology diffusion under imperfect competition

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Chapter 10

Synthesis

10.1 Summary and conclusions

The focal point of this thesis is the diffusion incentives of environmental policy instruments. Emission taxation, subsidies per unit of emission reduction, marketable emission permits and marketable emission credits are discussed and compared to each other on how they affect the diffusion of clean technology in the long-run. The major innovative feature of the study is the dynamic approach of the problem by conducting the analysis within an applied evolutionary game theoretical framework. Although evolutionary views have inspired a number of economists from the early beginnings of economics as a discipline, the formal framework of evolutionary game theory has been developed by biologists from the early 1970s on. Economists recognized fairly soon that their methodology could fruitfully be applied to economic problems thus providing a dynamic supplement to (static) neoclassical analysis.

Methodology

The methodology is outlined in chapter 2. The basic concepts from evolutionary games in biology have their counterparts in economics. For example, a population can consist of competing firms which can play different strategies. These strategies may yield either a high or low payoff, depending on the shares of firms playing the distinct strategies. A striking parallel between the biological and economic versions of evolutionary game theory is that optimal outcomes result from a selection mechanism, making that the fittest category survive. The basic evolutionary idea in economic games is then, for example, that strategies with high profits crowd out strategies that yield lower profits. Such an adjustment process (selection dynamic) might lead to an evolutionary equilibrium, which coincides with the (static) Nash equilibrium.

The major contribution of evolutionary game theory to economics lies in the first place in a superior, more general modelling of adjustment processes and in the discussion of the stability of the attained equilibria. The equilibria predicted by the evolutionary model are suitable for empirical testing since it is most likely that the empirical evidence comes from states near evolutionary equilibria.

Diffusion models and evolutionary game theory

Chapter 3 provides an overview of the models that have been used to describe and explain the diffusion of innovations. The epidemic model, the probit model, the classic game theoretic model and (general) evolutionary model are discussed. Each category of models has its own shortcomings. The classic epidemic model gives a quantitative description of diffusion, but does not provide an underlying economic decision making framework upon which diffusion is based. Probit models do have an economic underpinning, but do not take into account the strategic setting in which the technology adoption decisions take place. Game theoretic models do bring the strategic environment into picture which is ignored by both epidemic and probit models. On the other hand, game theoretic models ignore the information spreading factors, which epidemic diffusion models explicitly take into account. Evolutionary or Neo-Schumpeterian diffusion models allow room for the complex network of interactions between technology on the one hand and economy on the other. Due to this, it is a rather qualitative framework. But in contrast to neoclassical theory, it provides an explicit interdependent relationship between the individual actor and the population of which the actor is a member.

Given all these different approaches to model diffusion, we introduce an evolutionary game model in chapter 6. This model synthesizes the positive characteristics of all four approaches: the epidemic model, the probit model, classic game theory and the evolutionary approach. Consequently, the evolutionary game model is more complete, making the overall framework more valuable. The evolutionary game approach should not be regarded as a substitute but as complementary to the four mentioned models. An economic evolutionary game approach brings together: (a) strategic interaction, (b) economic orientation and (c) endogeneity of 'contagiousness'. We shall briefly sketch the main ingredients and show to what particular diffusion model it is attached and in what respect it complements the previous approaches.

An evolutionary game refers to any model of *strategic interaction over time* with the features of *monotonicity*, *inertia* and *Game Against Nature*. So, the evolutionary game approach to study diffusion should embody strategic interaction. In our approach, the interaction consists of two parts. First, the technology choice between a new 'clean' technology and an old 'dirty' technology, where a number of adopters will imitate the example set by the most successful firm. Second, the clean and dirty firms interact with each other in an imperfectly competitive product market where they compete in outputs.

Furthermore, strategic interaction occurs over time, implying that the game is played repeatedly. In this sense, an evolutionary game approach complements the static one-shot game approach of e.g. Reinganum (1981a, 1981b, 1983). An essential ingredient of the dynamics of diffusion in an evolutionary game is the monotonicity principle. Monotonicity implies that lower payoff strategies are wiped out by the higher payoff strategies. In case of a choice between a clean and a dirty technology, the selection mechanism reflects that the choices of the successful firms are imitated, thus decreasing the share of the other category of firms. Hence, the dynamics refers to the strategy level *and* also to the repeated interacting nature between players.

By explicitly defining and incorporating an adjustment dynamic, diffusion models based on evolutionary game theory can gain insight into *how* the equilibrium degree of diffusion becomes established; whereas static classic game theory solely focuses on the existence and analysis of the equilibrium itself. The adjustment dynamic is attached to the Game Against Nature element, implying that players do not systematically attempt to influence the future behavior of other players. In our model, the technology adoption decision of the firms is based on following the example of the most successful firm and the firms do not make plans to change the decisions of other firms systematically. The same is true for the output market, which is part of the diffusion model and is modelled as a Cournot oligopoly. Players in such markets do not try to influence the quantities set by their competitors, but accept them as given.

Finally, the inertia element is automatically fulfilled since diffusion of technology is a slow process and often reflected by a gradual change in population of adopters. With the inertia assumption we rule out radical technological regime shifts as in e.g. Kemp (1997).

Environmental policy: adoption and diffusion incentives

After the more methodological oriented chapters 2 and 3, the attention is directed towards environmental policy in chapter 4. Up to now, the theoretical literature dealing with the diffusion of pollution control technologies (clean technologies) induced by environmental policy, have mainly followed a partial and comparative static analysis, comparing equilibria before and after the introduction of a pollution abatement technology. As a result, the focal point in the analyses are the equilibria itself rather than investigating the qualitative behavior of the adjustment path that may lead to the equilibria. This branch of work can basically be divided into two parts: one focusing exclusively on pollution control, which neglects the output market and the other taking an explicit notion of such markets. The bulk of literature is in the first category.

The clean technology is reflected by an overall decrease in the pollution control cost curve and promises therefore higher profits to its adopters. The question is then which instrument of environmental policy raises profits of innovation most. That particular instrument would provide the strongest incentive to adopt the clean technology. We have identified big differences between authors in their ranking orders of different environmental policy instruments, given the effects on the adoption and diffusion of clean technology. The analysis underlying the established ranking orders is frequently based upon flawed assumptions such as not taking into account the opportunity costs of grandfathered tradable emission permits, or as incorrect reasoning like imputing the effects of a lower permit price only to the adopters of the pollution control technology.

Within a comparative static framework, our first conclusion is that the ranking order depends on the assumed price or tax level, given the emission target the industry faces. If the ‘old’ price (*before* the introduction of the clean technology) is used and output effects are neglected, then all four market-based instruments (auctioned and grandfathered emission permits, emission taxes and emission reduction subsidies) perform equally well and their adoption incentive exceeds the incentive emanating from direct regulation. On the other hand, if the ‘new’ price of emissions (*after* introduction of the clean technology) is used, the ranking order is reversed: direct regulation provides a higher adoption incentive than the market-based instruments.

The second conclusion is that a purely comparative static analysis is not a very enlightening approach in order to provide adequate policy advise on which instrument performs best in stimulating the diffusion of clean technology. A dynamic analysis is needed to see what happens between start and finish of diffusion and how the adoption incentive and actual diffusion evolves during the adjustment period from the old to the new equilibrium. This pertains in particular to the tradable permit instrument since permit prices will change during the process of diffusion of clean technology. Consequently, the adoption incentives develop differently than the impact of emission taxes or emission reduction subsidies. It illustrates that without a dynamic analysis, less well-founded predictions can be made on which instrument will be the ultimate winner of the race.

The third conclusion of chapter 4 is that the diffusion analysis should not only investigate the pollution control decisions of firms and industry, but also its repercussions on output markets and its feedback to pollution control. This applies to both perfect as well as imperfect competitive output markets. So, the interaction between technology choice and the decisions on output and prices in the product market should not be neglected.

Evolutionary game models of imperfect competition

In chapter 2, which described the theory of evolutionary games, it came forward that the methodology is quite appealing to analyze strategic interaction in market environments characterized by perfect competition. In such non-concentrated markets, the pressure comes from the firm's direct competitors. It forces him to produce efficiently (profit maximization) in order to survive (natural selection argument). In this thesis we explicitly focus on a concentrated market structure instead. Chapter 5 explores how evolutionary game theory can be used for such a market setting. An overview of the main literature dealing with economic natural selection within imperfectly competitive markets is given. The key issue of this literature, which is restricted to basic Cournot and Bertrand models, is whether partially informed imitators can survive in the long-run and thus can coexist next to fully informed profit maximizers. Another question is whether in oligopolistic market settings, the adjustment process tends towards a marginal cost-pricing (Walrasian) outcome or a 'classical' profit maximizing equilibrium of Cournot and Bertrand oligopolies. The general finding is that in imperfectly competitive markets the outcome often constitutes a Walrasian equilibrium, where quantity and price decisions are based on imitating the decisions made by successful competitors.

Experimental studies support the conclusions of the theoretical research on the outcomes of evolutionary Cournot and Bertrand models. The group of authors following the trail set out by Schaffer (1989) and Vega-Redondo (1997), analyze firms which have limited information about market conditions and base their decision on the examples set by competitors. As a rule, they find that the Walrasian equilibrium is the evolutionary stable outcome. On the other hand, Qin and Stuart (1997) and other authors in this group assume complete information on all relevant market conditions. They find the Cournot-Nash equilibrium as the evolutionary stable outcome. Moreover, they also obtain a finding that Bertrand oligopoly may have an evolutionary stable outcome deviating little from the Walrasian outcome. This too is supported by results obtained in the experimental literature.

An evolutionary game model of technology adoption in a Cournot market

Chapter 6 is the start of the explicit modeling. In this chapter we have set up a framework suitable for generating and analyzing the diffusion process of a clean technology in a polluting industry with a restricted, fixed number of incumbent firms. Firms compete in an imperfect product market à la Cournot. Prior to setting profit maximizing quantities, firms choose to produce either by means of a dirty or clean technology. The clean technology differs from the dirty technology in generating lower emissions per unit of output. In this respect, the model differs from the literature discussed in chapter 4, which assumed that there is a continuous range of abatement options at increasing marginal cost from which the polluter can choose. Another difference is that our model does include the output market. Actually, the choice between a clean and dirty technology boils down to the choice between producing a dirty or clean product which compete as perfect or imperfect substitutes in the oligopolistic output market. The two products can differ in costs and/or in demand characteristics. In our base simulations it is assumed that the clean product has lower variable costs relative to the dirty product due to e.g. lower inputs of fossil fuels. Moreover, the clean product can also have a price advantage due to its positive image of being less pollutive than its dirty counterpart. The positive consequence of this construction is the explicit interaction between technology choice and output decisions. The quantities of clean and dirty outputs produced and sold are endogenous to the diffusion process and determine the volume of total industry emissions.

Different from the evolutionary game models of oligopolistic markets discussed in chapter 5, we assume that all firms make rational output choices, behaving as Cournot oligopolists that maximize their absolute profits. This implies that each firm has sufficient information about the costs of the chosen technology, the output of competitors and its own marginal revenue. The situation is different with respect to the technology choice. The firm is not capable to calculate ex ante which technology will yield higher absolute profits. This is a plausible assumption. For instance, firms that produce the dirty product variant have knowledge of their own costs and demand characteristics accumulated from past experience, but not of the clean product they have never produced. However, they do have sufficient information about profits of the clean product supplying competitors. Firms are assumed to be able to determine whether competitors obtain a higher or lower profit level and, subsequently, base their technology adoption decision on that information. Technology diffusion is therefore modelled as an evolutionary process on the basis of the short-run profit differential between firms producing clean, respectively dirty output; i.e., the number of firms using the technology with the higher short-run profit level tends to increase. Instead of *expected* absolute profits, *actual* realized relative profits drive the adoption or non-adoption of clean technology.

In chapter 6 we analyze the choice between a clean and dirty technology in a context without taking account of environmental policy. This is the so-called laissez faire policy regime. How the adoption of clean technology evolves over time depends solely on market forces, i.e., the supply and demand side of the output market. The solution of the model demonstrates that the profit differential is a decreasing function of diffusion, implying a unique interior stable Nash equilibrium for the degree of clean technology adoption (*cf.* McGinty, 2001). The short-run profit differential, defined as the difference between the profits received under clean production and the profits under dirty production, is positive for relatively low states of clean technology diffusion among firms. Hence firms tend to switch from a dirty to a clean production mode and the share of clean firms in the industry will increase. Firm-level profits when supplying the clean product decrease as more firms enter this clean submarket by adopting the clean technology. More generally, the benefits from technology adoption decrease as the number of users increase. The diffusion process halts when the profits under both technological modes are equal to each other and the firms are thus indifferent between them. This is the interior solution, which is the evolutionary stable long-run outcome of the diffusion process. It implies that both clean and dirty firms coexist in the long-run, i.e., both product substitutes coexist in the long-run.

Furthermore, we find that under laissez faire the equilibrium degree of clean technology diffusion is positively (negatively) related to a positive (ceteris paribus) change in the net absolute advantage of the clean (dirty) firm where the net absolute advantage is defined as the difference between the price intercept and the average variable costs, given the choice of technology.

Conclusion three: provided the clean (dirty) firm has a net absolute advantage over the dirty (clean) firm, a lower (higher) degree of product differentiation, i.e., a higher (lower) degree of product substitutability, will lead to a higher (lower) number of firms employing the clean technology in the long-run. As the clean and dirty product become closer substitutes, the product with the strongest competitive position sees its position further strengthened.

One of the most interesting findings is that diffusion of clean technology does not necessarily lead to a lower level of total emissions under the laissez faire regime. Different from what one intuitively might expect, pollution may even increase in the first stage of diffusion of abatement technology. Starting from the initial state of diffusion where all firms produce by means of the dirty technology, an increase of diffusion of clean technology induces a boost in the volume of clean output, which may exceed the decrease in dirty output. The increase in pollution as clean technology starts to crowd out the dirty technology implies that the production effect of higher emissions due to higher total output, offsets the positive substitution effect of switching from the dirty to the clean technology, which tends to lower emissions. However, as diffusion of clean technology progresses, the substitution effect will dominate hence total emissions decrease and in equilibrium total emissions may be higher or lower than before the introduction of clean technology. Such a development of initially increasing emissions only occurs if the emission/output ratio of the clean technology is not extremely lower than the emission/output ratio of the dirty technology. When the difference between the emission output ratios is sufficiently large, total industry emissions are strictly decreasing in clean technology diffusion.

Emission taxation and emission reduction subsidy

The Cournot model outlined in chapter 6, representing the laissez faire regime, is extended in chapter 7 by adding two alternative environmental policy instruments, namely a uniform emission tax and a subsidy per unit of emission reduction. For each of these pollution control policies it has been analyzed to what extent they stimulate the diffusion of clean technology, taking the laissez faire regime as a benchmark. Just as was assumed under laissez faire, the clean and dirty product are imperfect substitutes. Given the parameter restrictions provided in chapter 6, both policy regimes evolve towards a unique dynamically stable interior equilibrium, i.e., a stable mixture of clean and dirty type firms. Evaluating these equilibria on the basis to which they enhance the diffusion of clean technology, we find that relative to laissez faire, both the uniform effluent tax and subsidy per unit of emission reduction have a positive effect. That is, the share of firms applying the clean technology in equilibrium is higher compared to laissez faire.

In a simulation it has been shown numerically how aggregate output and the generated emissions evolve as a function of the diffusion process. When emission taxes are applied, total emissions are lower than under laissez faire for all diffusion states. For emission reduction subsidies the outcomes are sensitive to the relative pollution intensiveness of the two technologies. When the difference between the dirty and clean technology is not too large in terms of emissions per unit of output, the subsidy instrument can cause emissions to be even higher than they are under laissez faire at any given state of diffusion. This is due to the positive stimulus a subsidy gives to output. The subsidy stimulates the adoption of clean technology in such a case, but at the same time harms the environment. This result does not longer hold when the difference between the dirty and clean technology is sufficiently large. Given the state of diffusion, subsidies then generate a lower volume of emissions than under laissez faire.

The relative difference in emission coefficients of the two technologies also affect the qualitative change in emissions as diffusion of clean technology increases. If the difference is relatively small, emissions increase in the early stage of diffusion and only in a later stage emissions start to decrease. When the difference in pollution coefficients is relatively large, the volume of industry emissions is strictly decreasing in diffusion under the taxation as well as the subsidy regime. The substitution effect of switching from a dirty to a clean production process then outweighs the production effect.

Tradable permits and tradable credits

Chapter 8 explores the environmental policy instruments tradable emission permits and tradable emission credits. The fundamental difference between the two instruments is that under a system of tradable permits the overall industry emission target is fixed and independent of industry output. Under a tradable credit system the emission target is tied to industry output. The target for the industry is not to exceed a specified quantity of emissions per unit of output.

A tradable credit scheme is basically direct regulation by emission standards with credit trade, creating the flexibility for individual firms to choose a higher or lower emission/output ratio than the emission standard.

Under a tradable permit system, a more stringent environmental target by a lowering of the emission ceiling results in a higher equilibrium degree of clean technology diffusion in the long-run, provided the clean firm faces a net absolute advantage which is at least as high as the net absolute advantage of the dirty firm. This holds in a Cournot product market where the goods are either imperfect or perfect substitutes. So, a varying degree of product differentiation does not impose any constraints in supporting the adoption and diffusion of clean technology by introducing a more stringent environmental policy. Within a tradable credit system, the pursuit of a stricter environmental policy by tightening the emission standard also affects diffusion of clean technology positively. This result is invariant to the degree of product heterogeneity.

The time pattern of total emissions differ between tradable permits and tradable credits. Under a permit scheme, total emissions remain on the target level during the whole diffusion process. In order to realize this, the permit price has to change in such a way that total demand for permits equals the available fixed supply at any stage of diffusion. The typical time path of the permit price is to increase in the early stage of diffusion, thus checking the increase of total output which would have caused higher emissions. In the later diffusion stage the permit price is falling. When the instrument of tradable credits is applied, total emissions fall to a very low level in the very first stage of diffusion of clean technology. This is due to a dramatic fall in total output caused by a shortage of credits. As more and more firms switch to the clean production mode, credit scarcity diminishes and total emissions increase until the diffusion equilibrium is attained. As a corollary, the credit price drops from its initial high level and steadily decreases over time.

With respect to the tradable permit regime, we proved that as diffusion evolves from the initial state where the whole industry employs the dirty technology, the firm who adopts the clean technology is a permit buyer. It has been shown that this specific buyer/seller role continues until a certain diffusion state is reached, which is lower than the evolutionary stable diffusion equilibrium. As a result, the roles have changed in the diffusion equilibrium where the clean firm is a seller of permits and the dirty firm a buyer. This suggests that developing clean production when the market for products is imperfectly competitive not necessarily means that firm-level emissions decline as a result from the adoption of clean technology and hence the opportunity to sell a permit surplus. Rather the reverse situation occurs; investment in clean technology by the innovating firm implies permit buying in the early stage of the diffusion process. However, with credit trade, clean firms are always the sellers of credits and dirty firms the buyers.

In comparing the economic variables under the two policy regimes, the point of departure has been that both yield the same long-run equilibrium degree of diffusion. Then the emissions per unit of production under permits and credits are equal. In the diffusion equilibrium, the prices of both the clean and dirty product variant are higher under permits than they are under credits. The costs of emissions per unit of production are higher under permits since under credits only *excess* emissions involve credit costs and under permits *all* emissions bear permit costs. The credit instrument is therefore more attractive than permits from a consumer's point of view. Lower product prices under credits also involve a higher volume of total output, making the level of emissions also higher compared to a permit scheme. This makes the price for emissions in the equilibrium higher under credits relative to permits. What on the other hand comes out quite clearly is that a credit policy causes a much bigger shock to the industry than a permit scheme. Output of non-adopters of clean technology is almost wiped out in the early stage of diffusion due to credit shortage. The positive side is that through this process of creative destruction (Schumpeter, 1942), the diffusion of clean technology speeds up, as can be concluded from the much bigger profit differentials for credits than for permits during transition.

Instrument ranking

Chapter 9 evaluates a system of emission taxation, subsidies for emission reduction, tradable emission permits and tradable credits to see how they perform in stimulating the diffusion of clean technology in the long-run and in increasing welfare. In order to avoid an arbitrary comparison, we introduced an emission target which is equal for all four pollution control policies. For each instrument we subsequently determined the so-called 'constrained evolutionary equilibrium' (CEE), which is the equilibrium diffusion state that satisfies the emission target. The CEE is thus a direct measure of the diffusion incentive given a fixed emission target. Emission taxation and permits provide an equivalent diffusion incentive and the emission tax coincides with the permit price in the evolutionary equilibrium under permits in such a case.

A comparison of the dynamically stable CEE reveals that no unique instrument ranking exists. Which instrument provides the highest penetration of clean technology depends on the market (demand) structure, cost structure and the relative pollution intensiveness of the clean and dirty technology. When products are perfect substitutes and the clean firm has a net absolute advantage over the dirty type firm, (1) permits and emission taxes provide the biggest incentive, followed by (2) credits and (3) subsidies. In case the dirty firm has a net absolute advantage over the clean firm, the ranking becomes (1) subsidies, (2) credits and (3) permits and taxes. So, the instrument ranking switches depending on the demand structure and cost setting.

We have investigated the welfare impacts numerically. The instrument that generates the highest degree of diffusion is also closest to the welfare maximum. So there is strict complementarity of instrument choice maximizing diffusion and maximizing welfare. For a market structure that diverges not too much from perfect competition, the welfare performance takes the ranking order: (1) permits and emission tax, (2) credits, (3) subsidies. The ranking order is reversed with product heterogeneity and a stronger distortion due to oligopoly. In case of such a strong oligopolistic market structure, the analysis suggests a second-best policy. A ‘distorting’ environmental policy instrument - emission reduction subsidy - is applied to redress the distortion created by an oligopolistic market structure. This redress consists of stimulating output, which is held back by profit maximizing oligopolistic firms; there is a boost from the emission reduction subsidy, which indirectly stimulates the demand for clean products.

As a consequence, the instrument choice entails an awkward complication for the policy maker. To be able to impose the most suitable instrument for stimulating diffusion (and by that welfare) as much as possible, the policy maker needs to have adequate information about the market structure, the pollution intensiveness of the technologies and even information on private costs. A lack of information about this implies a weakening of the policy basis to initiate the right incentive. To make policy decisions even more complicated, the policy maker should not only look at the ultimate equilibrium position, but also at the economic adjustment pains it may cause and the pattern of emissions during diffusion.

In the welfare maximizing case, dirty output is crowded out completely, leaving no room for the dirty technology. Knowing that welfare maximization reflects solely the supply of clean products, we can say that under imperfect competition there is not only too little production (as is commonly known), but that there is also too much supply of dirty output. Considering the lack of up-to-date information on the specific features of the market, that is, the level of product differentiation and the firm’s relative absolute advantages, the most sensible way to proceed is a general competition policy, which eliminates barriers to entry for new firms, aiming at workable competition and applies first-best instruments in its environmental policy. That is, environmental taxes or the politically more feasible instrument of grandfathered permits to stimulate the adoption and diffusion of clean technology.

10.2 Discussion and research agenda

Evolutionary game theory is applicable as a tool to study technology diffusion when there is fundamental ex ante uncertainty among potential adopters about the performance of the new clean technology, relative to the old dirty technology. The uncertainty may pertain to the demand conditions, costs of new technology, risks of breakdown and to the technology choice of competitors. Given the lack of information ex ante, profit maximizing calculations cannot be made. But what firms can do is to observe the success or failure of competitors, comparing the performance of adopters and non-adopters of innovative technologies. Ex post information on profits of adopters and non-adopters can be the incentive for a number of firms to switch technological production modes. In the model discussed extensively in chapters 6 to 9, technology switching was based on the sign of the profit differential [see equation (6.23)]; if profits of adopters of the clean technology exceed the profits of non-adopters, the number of adopters grows and vice versa.

The focal point of the thesis was to determine the long-run diffusion equilibria generated by different environmental policy instruments within imperfect competitive markets. Due to this, the examination of the time paths of diffusion under these pollution control policies is essentially implicit in nature. In turn, also the time length of the transition periods towards the diffusion equilibrium was not part of the analysis. This remains as a topic for future research.

Time path of diffusion

The dynamic analysis in this dissertation contained the evolution of clean technology adopters based on a short-run profit differential, i.e., $ds/dt = \Delta\pi(s)$ (see section 6.4). Given the setup of the underlying economic model of a heterogeneous Cournot market, the profit differential is decreasing in the fraction of clean technology users. This implies that the more firms adopt the clean technology, the lower the difference between clean and dirty firm profits. From this differential equation [see equation (6.26)] it is possible to derive a time path of diffusion, which describes how the fraction of clean technology adopters evolves over time. It is then also possible to determine the time period that it takes for reaching the evolutionary stable diffusion equilibrium. Given the specific market setup, solving this particular differential equation will generate a concave increasing function $s(t)$. Recall that the diffusion pattern $s(t)$ found in the empirical literature is often of a sigmoid type. So, the model presented in this thesis shows only resemblance with the second part of a sigmoid diffusion pattern.

We will suggest that with a minor modification it is possible to derive such a specific diffusion pattern, however. The only thing that we need is a logistic function. Recall that the classic logistic function is of the form as in equation (3.1), i.e., $ds/dt = \xi s(1-s)$, where ξ refers to the speed of adjustment, which is assumed to be fixed in the classical case. In our model, s represents the share of firms that has adopted the clean technology, with the diffusion dynamic specified as above ($ds/dt = \Delta\pi$). The speed of adjustment is here represented by the profit differential $\Delta\pi$. If we multiply this term with $s(1-s)$, we obtain a logistic function which is even a better version than the classic one since the speed of adjustment $\Delta\pi$ is not an exogenously determined parameter as ξ is, but endogenous to the fraction of clean technology users, which in turn is based upon the underlying economic Cournot model. Both versions, i.e., $ds/dt = \Delta\pi$ and $ds/dt = s(1-s)\Delta\pi$, will lead to the same interior diffusion equilibrium; however, the transition period to this diffusion equilibrium may be different. Solving the differential equation $ds/dt = s(1-s)\Delta\pi$ would lead to the empirical sigmoid diffusion pattern[1]. So, the advantage of $ds/dt = s(1-s)\Delta\pi$ is that now also the first stage of the diffusion pattern can be determined. Therefore, evolutionary game theoretical models are able to derive sigmoid diffusion patterns. In addition to solving the differential equations that specify the dynamics of diffusion, analyzing specific versions of the dynamic is also left for future research.

In relation to this, interesting future research might be to test empirically the underlying economic model and the diffusion patterns. In this line of research one can also determine the speed of adjustment in particular imperfect market settings. So, the research involves the derivation of the specific diffusion dynamic. One could test under which conditions $ds/dt = \Delta\pi$ and $ds/dt = s(1-s)\Delta\pi$ are appropriate specifications. Such an analysis gains

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[1] The differential equation $ds/dt = s(1-s)\Delta\pi$ is a representation of the so-called *replicator dynamic.*

insight into the length of the transition period towards the evolutionary diffusion equilibrium within these market settings. Taking a first intuitive glance, one has to remember that the first and progressively increasing part of the sigmoid function reflects the increasing number of adopters due to more and more sources of information as s grows; the second and degressively increasing part of the diffusion curve is explained by the decreasing number of members of the population that are still uninformed. It is reasonable to argue that the actual spreading of information measured by the term $s(1-s)$ plays a more prominent role when the population of potential adopters is relatively large since it will take time to spread the new information. On the other hand, in a small population such as an oligopolistic market, information (on the payoffs of using the clean and dirty technology) is probably faster available to all firms in the industry. If this is indeed the case, this may plead for taking a diffusion dynamic of the form $ds/dt = \Delta\pi$ when there are only a few players active in the population. The paper by Arthur and Lane (1993) may be an interesting starting point to investigate the above issue.

Other model extensions

The presented evolutionary game theoretical framework has room for other extensions as well. First, the model presented in this thesis involved two technologies. An extension could be to model an additional strategy where firms can produce their outputs with two different technologies simultaneously. So, being either clean or dirty, a firm can choose to be an 'intermediate' by supplying both types of goods on the market, implying the coexistence of both the clean and dirty technology within a single firm. Second, the model can be enriched by the inclusion of an entry/exit mechanism, making the population size endogenous. Third, throughout the thesis it was assumed that firms can supply their profit maximizing quantities without facing any capacity constraints. An extension can be to include such constraints and see how this affects the model. This implies that after the choice of technology and prior to determining the level of output, a firm has to decide on how much to invest in capacity. Fifth, the model only emphasized the diffusion stage of technology. Next to this, Schumpeter (1942) also distinguished an innovation and invention stage. Taking account of these two stages, in particular the inclusion of R&D activities of firms, might be an interesting extension. Sixth, the model is one-dimensional, i.e., only one population of actors is examined. The consumer market was modelled implicitly. An extension could be to model the consumers explicitly as a different population. For example, it might make sense to model the gradual diffusion of knowledge about the new (clean) product among consumers, i.e., a gradual increasing demand curve for clean products. Moreover, in this thesis firms can reduce emissions per unit of output only by switching from a dirty to a clean production mode. It would be interesting to generalize the model by introducing a continuous emission control function for dirty output and a lower control cost function for clean output. It then can be investigated whether this leads to conclusions different from those in this thesis. Finally, policy makers should keep in mind that a partial analysis of instruments, as in this thesis, can be misleading to some extent. For example, the picture in this thesis suggests that taxes are far more effective in bringing down emissions than subsidies. However, taxes can be spent by the government, thus increasing pollution; subsidies require additional taxation elsewhere, thus reducing output and emissions. The natural question then is: what is the net overall effect? By extending the model to a general equilibrium analysis a possible answer to this question could be provided (see e.g. Toman and Withagen, 2000).