Overcoming lock-in for the transition to distributed energy production systems: the case of micro-cogeneration at households

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Abstract

The introduction of distributed, de-centralized energy production systems is often considered to be less polluting and more efficient than large scale production units. The distributed energy system can contribute to reduce various polluting gas emissions and enhance security of energy supply on a national level. However, the introduction of this system clearly requires a major institutional transformation.

In order to identify the opportunities and bottlenecks for such a transition, we have formulated a preliminary evolutionary simulation model to examine the conditions under which technological successions can occur. In our model, two technologies compete for adopters by means of their fitness, which is determined by an implicit set of characteristics, as well as by their market share. The technology fitness will evolve according to the adoption of the technologies.

We use the model to study the diffusion of micro-cogeneration, a technology that provides heating as well as electricity production at the household level. It is intended to replace present decentral gas-fuelled heating systems as well as (partly) replace centrally produced electricity. Diffusion of the micro-cogeneration technology not only involves the substitution of one heating technology by another, but also requires attaching the technology to the electricity grid. Following the scene set here, the two competing technologies in the model are characterized by a high market share for the old technology and by a low market share for the new technology. However, the new technology has an additional quality feature (namely electricity production), which increases its attractiveness and therefore its fitness.

Micro-cogeneration is now in its demonstration phase in the Netherlands. Momentum in the market is presently increasing, but national government is yet undecided on support measures. Our current model allows to qualitatively examine some key conditions under which a technological succession can occur, which can be helpful to study the effect of various policy measures.

Introduction

Technological development is embedded in its socio-economic and institutional context: a technology and its environment evolve in interaction with each other. This linkage implies that a system's perspective is needed in order to understand and assess technological development in its surroundings. Evolutionary economics provides a useful framework for the assessment of technological development in complex dynamic systems. An evolutionary approach involves a number of crucial characteristics:

- Bounded or imperfect rationality of heterogeneous agents leads to a diversity of strategies, technologies, firms, etc. Even fully rational agents prefer to follow a satisficing strategy rather than an energy consuming optimizing strategy, because they are constrained in time and opportunity to explore all relevant alternatives in order to find the optimal strategy;
- An evolutionary system involves the existence of multiple equilibria in a dynamic system, rather than a single, stable equilibrium. Equilibria alter as a result of change in the system and are therefore rarely reached. Rather, they function as attractors in the system;
- The carrier of the evolutionary trait is subject to birth, death and reproduction in the biological context, or to innovation, exit (bankruptcy) and imitation in an economic context. These features are all subject to a certain degree of persistence of random events;
- Events usually depend upon the cumulation of previous events, which leads to a path dependency of actions.

Given these characteristics, evolutionary models provide new tools for the analysis and layout of environmental innovation policy, specifically when addressing the initiatives under the heading of transition management, which explicitly aims to trigger changes on the system level (Frenken, Faber & Idenburg 2006). Evolutionary simulation models are especially useful to assess and understand the relevant mechanisms at work in a social process, rather than focusing solely on the outcomes.

In this paper we present an evolutionary simulation model, with application on cogeneration of heat and power at the household level (micro-CHP). The modelling of micro-CHP could help to draw generic lessons on the technological development of distributed (decentralized) energy systems, as well as for the study of the role and development of niche markets. Our research will help to gain some understanding on issues such as: the timing, conditions and mechanisms with respect to technology adoption and a shift to distributed energy production, the role and characteristics of niche markets, the roles of producers and consumers, and the complementarity between the electricity and the thermal energy regimes at the household level. Finally, we aim to explore some opportunities and pitfalls of evolutionary modelling for technological development and environmental policy making in general.

The outline of this paper is as follows: the next section will briefly sketch the specific technological and socio-economic features of micro-CHP, proceeding from earlier study of this technology (Elzenga, Montfoort & Ros 2006). We will provide some remarks on government intervention with respect to this technology. We will conclude with some preliminary results and propose an outline for an evolutionary model of technology substitution by the use of niche markets for energy systems.

Micro-CHP and some general features of distributed energy systems[1]

Technology description and socio-economic context

Cogeneration (CHP) is a technique whereby excess heat released in industrial processes or in centralized electricity generation is captured and turned into a useful application, such as domestic or industrial heating purposes. CHP thus uses heat that would otherwise be wasted in a conventional power plant, potentially reaching an efficiency of about 70% or even more in the best applications, compared with around 40% for conventional plants. In the Netherlands, CHP provides an important share in national electricity capacity

Micro-cogeneration (micro-CHP) is a small scale variation on this concept, co-generating heat and electricity at household level. In contrast to most industrial CHP plants, first generation micro-CHP generally meets the need for heat, with electricity production as the secondary product. Micro-CHP is therefore usually designed to replace conventional domestic heating systems, with the additional feature of electricity production (*Figure 1*). Electricity produced in this way can be used within the home or business, or (if permitted by the grid management) sold back into the electric power grid. A thermodynamic efficiency of more than 98% is conceivable for a micro-CHP system, if heat production is applied in a similar way as with conventional gas-fuelled high efficiency (HR) heat production for households.

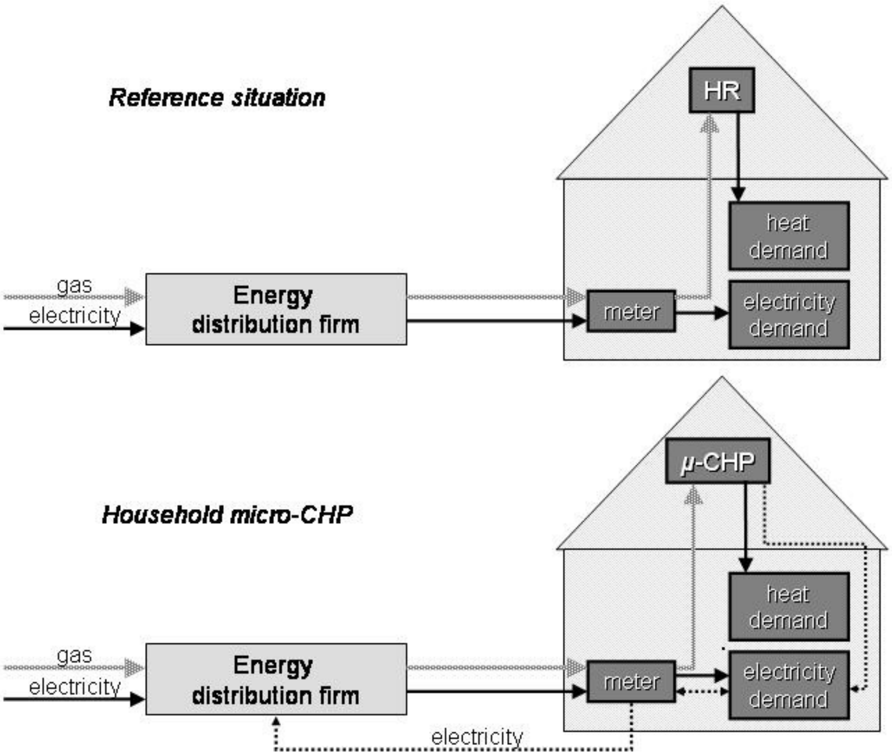

Figure 1 Household energy flows in a reference situation and with micro-CHP

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[1] This overview is based on the following resources: Van Hilst (2005), Overdiep (2005), Elzenga et al (2006), Werkgroep Decentraal (2006), Taanman (2004); interviews in 2007 with Gert-Jan Zijlstra (Ecofys) and Philip Lely (Essent); interview with Henk Sijbring (SPF) in magazine *Installatie & Sanitair* 2 (Feb. 2007), pp. 14-15; technology descriptions in Wikipedia.com, ecn.nl and howstuffworks.com

Various technologies can be used to produce electricity in a micro-CHP unit:

The *Stirling engine* is an external combustion motor, characterized by the use of an external heat source and by the fact that the gases used are internal to the engine. Stirling engines are very quiet, since no combustion takes place inside the cylinders of the engine. In principle, any fuel source can be used to power the heat source. A shortcoming of Sterling engines lies in its slow response to changes in the heat applied, which inhibits application where such changes are crucial, such as in cars. Stirling engines have therefore never found successful mass-market production and its application remained in niche markets, e.g. as auxiliary power generators for yachts. Electric efficiency of the Stirling micro-CHP in most prototypes remains at a relatively low 10-18%, while thermal efficiency is about 90%. Stirling engines have a relatively high heat-to-power ratio (HPR), thus producing excess heat rather than excess electricity. Thus, if thermal energy demand is leading, net production of electricity will be lower than needed and additional electricity intake from the grid will be needed.

The *Otto engine* is an internal combustion motor, similar to those applied in most cars. In the internal combustion engine the fuel is compressed and combusted with a spark plug, together with an oxidizer (typically air) in a confined space called the combustion chamber. This reaction creates gases at high temperature and pressure, which expand and thereby act on pistons to move the engine, after which the gases are exhausted. Most commonly gasoline or diesel is used as a fuel, but other fuels can also be used, such as natural gas, ethanol, hydrogen or biodiesel. Otto gas engines are already applied widely in larger scale CHP-systems, for example in greenhouses, but they are not yet well suited for micro-CHP applications. Presently, pilot gas engine micro-CHP systems show an electric efficiency of around 20% and a thermal efficiency of up to 75%.

A *fuel cell* produces electricity from an external supply of fuel (usually hydrogen) on the anode side and an oxidant (usually oxygen) on the cathode side, which react in the presence of an electrolyte and a catalyst. Before this process, a reformer is needed to convert (in most cases) natural gas to hydrogen, thereby releasing water, CO and CO_2, as well as decreasing the overall efficiency of the process. Fuel cells produce a direct electricity current (DC), rather than alternating currents (AC), which requires application of a relatively expensive convertor after the process. A major advantage of fuel cells is the possibility of modular application in so-called stacks, gearing them to specific demand. Various types of fuel cells exist, characterized by the material of the catalyst and the temperature of operation, which in turn defines their vulnerability to pollution in the fuel (typically carbon monoxide) as well as their start-up time. Presently, the application of fuel cells in micro-CHP is still far from market introduction and generally considered to be the second generation of micro-CHP systems. In the meantime, development of fuel cells is believed to be able to profit from research for other applications, e.g. in cars, in notebook computers or as a general off-grid power supply. Fuel cells have a relatively low HPR, producing excess electricity rather than excess heat. In other words, if thermal energy demand is leading, production of electricity will be higher than needed and require either storage or feedback to the grid. The types of fuel cells most applicable in micro-CHP have an electric efficiency of well over 30%, and a thermal efficiency of more than 60%, both still considered to have room for further improvements.

Table 1: Classification of agents involved in micro-CHP in the Netherlands

Category	Function	Main players	Main interest with respect to micro-CHP	Innovation system function addressed
Energy retailers	distribution and retail of energy; energy services	Gasterra, Essent, Nuon, Eneco	- maintain and extent gas infrastructure connectivity; - focus on energy services, incl. strategic partnerships with e.g. fitters; - security of electricity production; - secure good price for electricity	1,4,5,6
Manufacturers	manufacturing conventional domestic heating systems and micro-CHP	Whispergen, Remeha, Vaillant, Bosch, Nefit, Enatec, Rinnai, Microgen	- maintain market position for domestic heating technology; - technological challenge; provide high performance technology	1,2,5,6
Fitters/ installers	installation of domestic heating devices	many	- maintain contracts with energy providers; - specialization, knowledge transfer from manufacturers	1,6
Intermediaries	network, knowledge diffusion, promotion	Cogen, SPF	- lobby and promotion of micro-CHP; - diffusion of knowledge	3,4,5,7
Housing corporations	Provide housing at relatively low cost	many; regionally or locally organized	- secure energy supply system at low costs in rental houses; - could act as a launching customer	5
Customers (households)	End user	categories: urban/rural, new/old houses.	- comfort; - high performance; - reliability; - low price	5
Government	Social planner	National government; political agents	- stimulate innovation; - maintain stable electricity grid; - energy security (energy policy); - reduce emissions (climate policy).	3,4,7
Research institutes	Research	ECN	- research	2,3

Many agents and instititutions are involved in the development, marketing and application of CHP systems in the Netherlands (*Table 1*), together making up an innovation system. An innovation system can be described by the functions it addresses (Hekkert et al. 2007): 1. entrepreneurial activities, 2. knowledge development, 3. knowledge diffusion, 4. guidance of the search, 5. market formation, 6. resources mobilization, 7. creation of legitimacy. All these functions are addressed in the micro-CHP innovation system. Our research does not aim to investigate whether all these functions are addressed with equal importance and in various stages of the innovation process, and whether a proper coordination among these functions is inhered to.

Environmental effects

Environmental benefits of micro-CHP primarily relate to the substitution of relatively polluting fuels (coal) by cleaner fuels (natural gas). To a much lesser extent, there may also be some advantage of avoided efficiency loss in transportation of electricity, although such losses only account for a few percent in relation to overall production. Moreover, efficiency of centralized electricity production (~45%) is much higher than electricity production with micro-CHP, which is still well below 20%. However, the CHP feature ensures that energy otherwise lost is used for heat recovery, yielding a high efficiency relative to the energy input.

If half of the 7.1 million Dutch households would use a Stirling-engine micro-CHP, it is estimated that about 1.4 billion m^3/year of natural gas could be saved, relative to central electricity production based on natural gas. This figure reflects an emission reduction of almost 2.6 Mton CO_2 per year (1.2% of annual Dutch CO_2-emissions), or almost 10 Mton when compared with the actual production plants, which mostly use coal rather than gas (Elzenga, Montfoort & Ros 2006). Increases in efficiency of electricity production by micro-CHP due to R&D and changes in household electricity demand have not been taken into account in this rudimentary calculation, suggesting that this is a low estimate is of potential environmental benefits. On the other hand, however, it should be noted that the market penetration estimate (50% of all households) is in no scenario foreseen to be reached before about 2030.

In addition to carbon dioxide, modern HR heating systems release about 20g NO_x per GJ of energy produced. Such a performance can also be assumed for the thermal component of Stirling engine micro-CHPs, which use burners equivalent to HR systems. For gas engines a similar performance is also possible, provided that a relatively expensive end-of-pipe catalyst is used to remove NO_x from the flue gases. Centralized electricity producers are subject the national NO_x emission trading scheme, a framework which for 2010 states a cap of 40g NO_x per GJ of fuel used. This translates on average to 93 g NO_x per GJ of electricity produced, based on the fuel mix that presently feed the electricity production plants. Micro-CHP could therefore lead to a considerable decrease in national NO_x-emissions. If half of Dutch households would be equipped with an micro-CHP by 2030, an annual NO_x emission reduction of about 5.8 kton/year has been be estimated, about 1.5% of annual Dutch NO_x-emissions (Elzenga, Montfoort & Ros, 2006).

General features, tradeoffs and dilemmas

Development and diffusion of micro-CHG involves a number of considerations, tradeoffs and dilemmas, which are important to take into account not only for further modelling excercises, but also for framing policies with respect to this technology:

1. Annual household heat demand in the Netherlands requires about 4,4 times as much energy as electricity demand. This HPR is in most scenarios estimated to decline in the future, as heat demand will decrease due to improved housing insulation, while electricity demand will increase due to higher numbers of applications. In comparison to that, Stirling engines have a HPR in the range of 4-9, the HPR of gas engines is 3-4 and for fuell cells it is 1-2. Generally, a micro-CHP will operate heat demand driven, thus yielding excess electricity with Stirling engines and possibly also with gas engines. Excess electricity production can be stored in (expensive) batteries, but may also be fed back to the

grid, which is potentially much cheaper, provided that some additional institutional regulation is made to organize a proper system of feedback tariffs.

2. Feedback to the grid is subject to large annual and daily fluctuations, which may seriously threaten the grid stability due to gaps between production and demand.
3. The cost-effectiveness of micro-CHP for households depends largely on the amount of heat used, a parameter destined to decline in importance in the future (see #1). Household energy use generally depends on various socio-economic indicators, such as household size and income: larger households and higher income groups tend to have a higher energy use, although large differences exist within income groups (Vringer, 2005). Also, different housing types have different profiles for energy use, which makes micro-CHP attractive in older, less energy efficient houses, rather than in newly built, highly insulated buildings. In a modelling exercise a typology can be made in terms of housing types (cf. Taanman 2004) or in terms of socio-economic indicators of households, thereby defining niche markets for application of micro-CHP.
4. From the perspective of the energy distributing firms, the attractiveness of micro-CHP in new neighbourhoods links to the cost of applying a natural gas infrastructure in the neighbourhood. This attractiveness may be low for very energy efficient houses, to which it may even be attractive to use electricity for heating purposes.
5. Technologies compete with each other on many different dimensions, one of them being the price of inputs. Distributed electricity production fuelled by natural gas (or H_2) therefore has a disadvantage to large scale centralized electricity production plants, which are in many cases fuelled by much cheaper coal or biomass. This price difference may change as environmental regulation obligates carbon capture and storage in conjunction with coal fired plants, but otherwise competition between coal-fired central and gas-fired distributed electricity production gives an the former a price advantage.
6. The introduction of micro-CHP replaces existing technologies for the provision of heat as well as electricity. Essentially, this implies not only a technology substititution, but also the fusion of two different technologies, each with its own characteristics. Intuitively, this seems harder to diffuse in the energy system due to a double competition with technologies already embedded in the socio-economic energy system.

Rationale for government intervention

Given that micro-CHP classifies as an innovation with clear environmental benefits, there is an argument for public policy to promote its further development and marketing. This argument is reinforced by the idea that this innovation may offer economic opportunities for manufacturers, which for many governments is an incentive to stimulate firms in this particular sector. On the other hand, legitimation for government intervention may be impaired by questioning whether short-term measures are in line with long term strategies, which in our case may possibly be the case for Stirling engines, which can be regarded to be a first generation technology rather than a long term perspective. Generally, arguments for government intervention are provided by market or system failures. Market failures refer to the situation where the public nature of innovation benefits blocks private investments, while system failures refer to e.g. a malfunctioning infrastructure, lock-in effects or a lack of coordination (Faber, Kemp & Van der

Veen, forthcoming). These failures generally require a social planner with a long-term perspective and an aggregated view on the economy.

With respect to environmental innovations in general, the role of government could be to articulate demand, to stimulate the production and promotion of innovations, or to coordinate activities by various agents and institutions involved. In the case of micro-CHP, government intervention will have to take the tradeoffs and dilemmas into account, identified earlier in this paper. In addition, it should be noted that political uncertainty and the reduction thereoff often plays an important role in influencing the speed and direction of technological development in the phase of pre-development (Meijer, Hekkert & Koppenjan, 2007). Various policy measures can be used to address these issues, just to mention a few examples: subsidies for R&D in order to improve the product, financial support measures to facilitate introduction of micro-CHP to the market, regulatory measures to improve the grid feedback price of electricity produced by households, strict regulation on forced market size (cf. biofuels), propose the setup of covenants for fixing production standards, facilitate voluntary cooperative frameworks for the exchange and transfer of knowledge, etc. A key challenge for our project is to quantify these measures and apply them in a modelling exercise.

A model for technological substitution

In the following section we will develop an evolutionary simulation model, in order to study the effects of policy interventions to promote the use of micro-CHP. For this purpose, we have adapted and further developed an evolutionary model of technology hyperselection, which could help in exploring the conditions for technological development and substitution.

A classic model of substitution is by Fisher (1930), who describes natural selection between two populations, which could be organisms, but also technologies. Selection depends on the size of the population and the fitness of the technology. This model can be extended by including increasing returns of adoption, which leads to a model of 'hyperselection' (Bruckner et al. 1994). We apply this model to the substitution of an 'old' technology by micro-CHP. In our case, the old technology is the existing gas-fuelled domestic heating system (HR), combined with grid-provided electricity.

From a modeller's perspective, we can study policy effects in our model by reformulating the (relations between the) variables and parameters that are affected, thus exogenously reflecting government intervention on the system.[2] These policy measures all compound to an increase in attractiveness for micro-CHP, which is reflected by a larger 'fitness'.

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[2] It has been argued that government intervention should be endogenized in evolutionary modelling, or for that matter, in any modelling excercise where such an intervention plays an important role in the system's dynamics. This would be very useful if the dynamics of the system is the object of research, e.g. in ex post analyses. However, in studying 'what if'-questions that characterize many ex ante policy analyses, there is no methodological constraint in maintaining an exogenous approach to government intervention.

Core deterministic model

The core variable in the model is an old technology (HR), which at some point will be challenged into competition by a new technology (micro-CHP). The technologies are characterized by their *fitness* and by their *market share*. The fitness F_i of a technology i, where i = 1,2 for either technology 1 (old) or 2 (new), describes the attractiveness of the technology for consumers. The market size of the technology i is characterized by the number N_i of users of technology i. Shifts in this number depend on the size of the population/market N and the fitness of the technology. This can be described in the differential equation:

$$\frac{dN_i}{dt} = F_i N_i - k_0 N_i \qquad i = 1,2 \tag{1}$$

where the factor k_0 is defined in such way that the total population, i.e. the total market for technologies, remains constant:

$$N = N_1 + N_2 \tag{2}$$

This restriction defines a competitive condition between the old and new technology on the market, and leads to k_0 being equal to:

$$k_0 = \frac{N_1}{N} \cdot F_1 + \frac{N_2}{N} \cdot F_2 \tag{3}$$

i.e. k_0 can be interpreted as the average technological fitness over the total population. This illustrates that substitution model (1) is very similar to the conventional replicator dynamics which is used to describe frequency-dependent evolutionary selection (Nowak and Sigmund, 2004).

By inserting (2) and (3) in (1), we obtain:

$$\frac{dN_i}{dt} = N_i \cdot (1 - \frac{N_i}{N}) \cdot (F_i - F_{\sim i}) \qquad i = 1,2 \tag{4}$$

where $\sim i$ denotes the complementary index being equal to 2 if i =1, and equal to 1 if i =2. In other words: F_i - $F_{\sim i}$ is equal to ΔF.

The dynamics of N_i depend thus on the specific form of the fitness: in case of a constant fitness which is independent of the share of the technology, it is clear from (4) that technology i exhibits logistic growth (conquering the market if $F_i - F_{\sim i} > 0$ or disappearing from the market if $F_i - F_{\sim i} < 0$). In situations where fitnesses depend on the specific share of the technology, more intricate dynamics occur. E.g. when using mixed-growth expressions for the fitness as proposed in Bruckner et al. (1996):

$$F_i = E_i + B_i N_i \tag{5}$$

where the factor E_i refers to the marketshare-independent (linear) growth part, while B_iN_i accounts for the marketshare-dependent non-linear growth part, which leads to hyperselection effects (Bruckner et al. 1994, 1996). From (4) we can infer that the hyperselection-model has three stationary points ($dN_i/dt = 0$):

$$\begin{aligned} &1) \quad N_1=N \,;\, N_2 = 0 \\ &2) \quad N_1=0 \,;\, N_2 = N \\ &3) \quad N_1 = \frac{NB_2 + E_2 - E_1}{B_1 + B_2} \,;\, N_2 = \frac{NB_1 + E_1 - E_2}{B_1 + B_2} \end{aligned} \tag{6}$$

Equilibria 1 and 2 (one of the technologies dominates the full market) are stable. Equilibrium 3 (which corresponds to $F_1=F_2$) is instable: a slight change in any of the variables will disturb the equilibrium and move it to either 1 or 2. In our modelling exercise, the market is initially dominated by technology 1: $N_1=N$ i.e. equilibrium 1. This market is challenged by a new technology 2 which is e.g. initially present in a volume $N_2(0)$.

If $N_2(0) > \frac{NB_1 + E_1 - E_2}{B_1 + B_2}$ then the novel technology will penetrate the market and replace the old technology; if however $N_2(0) < \frac{NB_1 + E_1 - E_2}{B_1 + B_2}$ then it will disappear.

Some preliminary results

These analytical results are illustrated in simulations with a discretized version of the substitution model as presented in eq. (1) (using finite-difference discretisation by the Euler scheme). We have calculated the $N_1(t)$ and $N_2(t)$ curves for a basis situation with $N_1(0)=13$ and $N_2(0)=7$. Factors B_2 for the new technology are set at different levels ranging from 0.3 to 0.6 in each of the 100 independent simulations, i.e. for each new simulation B_2 is increased with a step of 0.003. The simulations represent a new technology starting with a smaller share of a market than the incumbent one, but with a better fitness. These simulations (*Figure 2*) show that in some cases (those with the highest fitness of the new technology), sales of the new technology quickly invade the whole market, replacing the share of the old technology. For smaller values of the fitness, the new technology takes longer to invade the market. For still smaller values of the fitness the new technology, although it is still superior to the incumbent, does not manage to overcome the initial block posed by its small level of sales. Therefore, sales of the new technology decline until disappearing altogether, the faster so the smaller its fitness.

It should be noted that quantification of factor B_i is for now an abstract measure representing a ‘driver of fitness’ for the technology, but in future analysis it will need to represent a more specific indicator, e.g. price, performance or environmental benefits. By doing so, we will make a more specific link between the technological description in the first part of this paper with the model description in the second part of this paper.

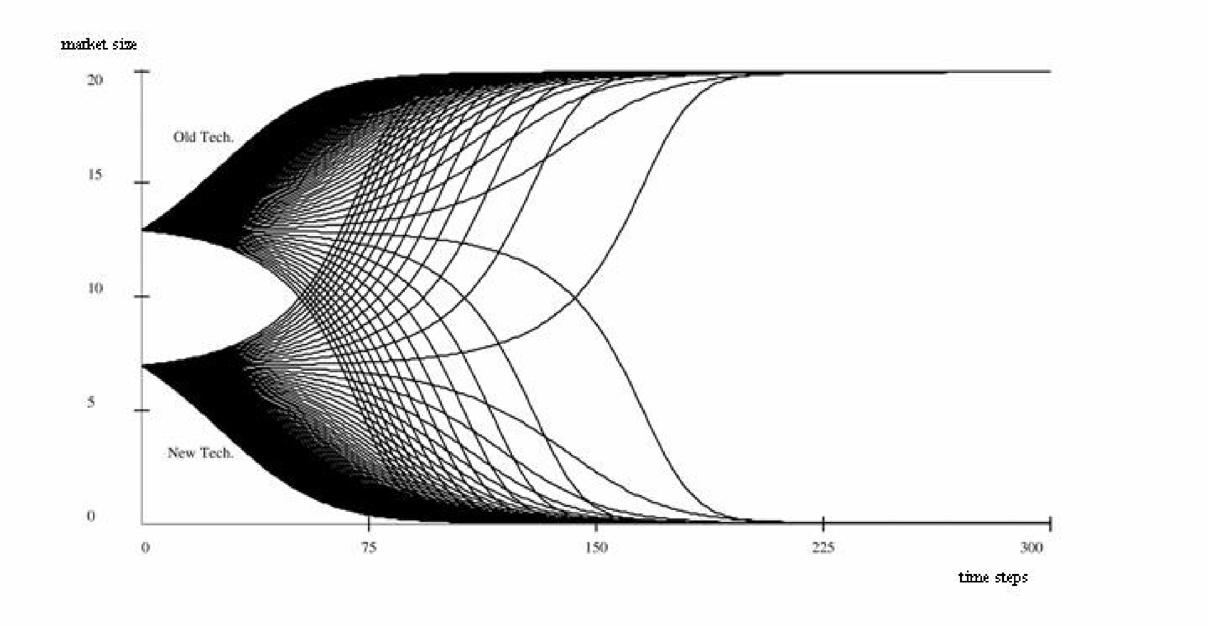

Figure 2 The series for N_1 and N_2 for 100 independent cases. In each case we use the following values: $N_{1,0}=13$; $N_{2,0}=7$; $E_1=E_2=0.1$; $B_1=0.3$; $h=0.05$.
h represents the discrete step size.

Fitness, as a measure of growth-potential (as expressed by the E_i, B_i) , per se is not enough to gain full market share; it also depends on its initial volume $N_2(0)$ whether the novel technology will prevail or not. In case that there is no linear growth part, i.e. $E_i=0$, the above mentioned condition for market-penetration requires that the novel technology has an initial marketshare:

$$\frac{N_2(0)}{N} > \frac{1}{1+\left({}^{B_2}\!/_{B_1}\right)} \qquad (7)$$

to take over the whole market.

Conclusions

These qualitative results of the model make sense:

- Firstly, the critical mass condition (7) illustrates lock-in situations that appear in non-linear growth dynamics with increasing return effects (due to B_iN_i): although novel technologies can have higher fitness than existing ones (as expressed by large values for the ratio B_2/B_1) it is no guarantee for their successfull market-penetration. Their initial share has to be substantial to establish this, e.g. for $B_2 /B_1 \approx 10$ about 1/10 th of the initial market should be early adopters of the novel technology.
- Secondly, the condition also points at the importance of niche markets for the survival and success of novel technology. In niche markets it will be easier to establish a critical mass for the new technology, and moreover niche markets can be selected in having a better fitness for the new technology.

In the micro-cogeneration case N is very large (7.1 million households), and the difference between B_1 and B_2 is still rather small, because economic gains of lower natural gas use are fairly limited and economic benefits for environmental gains are zero, since CO_2 emissions are not yet priced in the Netherlands. In such a case, thus assuming that B_2/B_1 is nearly equal to 1, it would require at least half of the households adopting the novel technology for full scale substitution to take place.

Several policy strategies can be envisaged to address the promotion of micro-CHP. The government can try to lower the critical mass condition, by either convincing large groups of people to adopt simultaneously (e.g., those living in social housing) or by creating or enhancing the formation of niche markets with a higher B_2 relative to B_1, which could first be conquered before further market penetration takes place. Convining large groups would require either for producers to increase attractiveness B_2 of their product, e.g. by lowering prices through subsidies or by increasing quality through supported R&D expenditures. Another option could be to set strict standards, forcing producers to manufacture a given amount of micro-CHP units.

Of course, the model here is still limited, because it does not take into account niches, where B_2 is actually much higher (e.g., in our case, large old houses and old public buildings). In the future we aim to study extensions of the model in this respect, adding new elements with specific dynamics, e.g. pricing strategies of firms affecting the attractiveness of technologies. In addition, an extension of the model with stochastic transition elements is considered, much comparable to Bruckner et al. (1994, 1996). Finally, we will need empirical evidence to parameterize the model and simulate results that can be validated.

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