Diffusion of combined heat and power in Dutch greenhouses – a case study

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Table of contents

Summary

This report presents the case study of the rapid diffusion of combined heat and power (CHP) units in the Dutch greenhouse horticulture in the period 2003-2009. The aim of the case study is to find explanations for this particular transition, and to generalize on the nature of technology diffusion processes. The study is carried out by means of a literature study, and by means of interviews with sector stakeholders, including several greenhouse growers.

In the theoretical framework, technology diffusion is conceptualized as a socio-technical transition, in which the interactions between different actors and the co-evolution of different societal domains form the key characteristics. We adopt a System-Network-Agent approach, as well as the theory of Universal Darwinism, in order to identify and examine the different developments and mechanisms that played a role in the CHP transition.

The case study generates three types of insights: observed phenomena, key drivers, and evolutionary mechanisms. These insights contribute to the understanding of the emergence and evolution of technology diffusion in industrial sectors, which may help the formulation of national innovation policy.

The five identified key drivers for the CHP diffusion are the opening of the energy market in 2002, the high spark spread during the transition period, the compatibility of output of a CHP unit with greenhouse demand, the flexibility provided by the heat buffer, and the cooperative and competitive greenhouse sector culture. We also found that the CHP diffusion has not been specifically aimed for by the Dutch government, but rather evolved out of interplay between developments in different societal domains.

A general conclusion on technology diffusion is that, given the existing variety in social-technical systems and the developments emerging in these systems, each technology diffusion case will necessitate a different degree and nature of government involvement in order for the diffusion to become a success. Therefore, innovation policy makers should consider the co-evolutionary mechanisms inherent in technology diffusion processes.

1. Introduction

This report is the final result of the historical case study 'CHP diffusion in Dutch greenhouses', which is part of the project Duurzame Greenport Westland Oostland (DGWO), funded by the Europees Fonds voor Regionale Ontwikkeling (EFRO). In the period 2003-2009, a rapid diffusion of CHP units in the Dutch greenhouse horticulture has taken place. The majority of Dutch greenhouse companies are located in Westland area. The aim of the case study is to find explanations for this diffusion, and based on that generalize on the nature of technology diffusion processes.

The case study generates three types of insights: observed phenomena, key drivers, and evolutionary mechanisms. These insights contribute to the understanding of the emergence and evolution of technology diffusion in industrial sectors, which may help the formulation of national innovation policy. Insights are generated first for the case of CHP diffusion in the Dutch greenhouse sector, where the total CHP capacity strongly increased in the period 2003-2009. After that, the insights are generalized to (sectorial) technology diffusion insofar possible. Technology diffusion is conceptualized as a socio-technical transition, in which the interactions between different actors and the co-evolution of different societal domains form the key characteristics.

In Section 2, the theoretical framework is presented, along with the research question. Section 3 includes the used methodology. Next, Section 4 contains the case study analysis. Then, the generated case-specific insights are provided in Section 5. Finally, in Section 6 the conclusion is presented.

2. Theoretical framework

Innovation can be defined as 'the application of new ideas to the products, processes or any other aspect of a firm's activities, and is concerned with the process of commercialising or extracting value from ideas' (Rogers, 1998). Although technological in nature, innovation is a societal process, taking place within a *socio-technical system*: A system, existing of a coherent whole of sub-systems and links with a single function or area, of which the relevant (network of) stakeholders are as much part as are the technical sub-systems. According to Rotmans et al. (2001), a *transition* is 'a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms'. After Chiong Meza (2012), we consider a *socio-technical transition* as 'a long-term process of social and technological transformation from one state of dynamic equilibrium to another'. In view of all these definitions, we can define ***technology diffusion*** as the transition process of the embedding of an innovation in a socio-technical system.

According to Rotmans (2003), a transition is 'a structural societal change resulting from the mutual influence and mutual reinforcement of developments in the domains of economics, culture, technology, institutions and nature & environment'. Loorbach (2007) defines a transition as 'a process of structural societal change from one relatively stable system state to another via a co-evolution of markets, networks, institutions, technologies, policies, individual behaviour and autonomous trends.'

We adopt the concept of co-evolution, and make a distinction between the five societal domains provided by Rotmans (2003): technology, economics, ecology, policy, and culture. Therefore, we define the ***co-evolution of societal domains*** as the interlinked and interacting developments of technology, economics, ecology, policy and culture in a socio-technical system. In this work, technology diffusion is thus considered a transition that emerges as a result of the co-evolution of societal domains (following the above definition by Rotmans (2003)).

Universal Darwinism (UD) is a theory which extends the application of evolutionary theory beyond the realm of nature. One of the ideas of this theory is that 'anything, anywhere, that displays variation, selection and heredity will evolve through natural selection, regardless of whether or not it is biological or alive' (Kasmire et al., 2011). Thus, according to UD, evolutionary mechanisms also apply to each of the (unnatural) societal domains in a socio-technical system: technologies, markets, policies, and even cultural concepts. Important evolutionary concepts and mechanisms are adaptation, variation, selection, and inheritance.
Universal Darwinism takes the concept of the co-evolution of societal domains one step further: Not only are societal domains considered to develop in an interactive way, but also do technologies, markets, policies and cultural concepts display evolutionary patterns known from biology[1]. We adopt the theory of Universal Darwinism, which means we look for natural evolutionary mechanisms in the case study 'CHP diffusion in Dutch greenhouses'.

The research question is the following: *How can the diffusion of CHP units in the Dutch greenhouse sector in the transition period 2003-2009 be explained, using the concepts of the co-evolution of societal domains and Universal Darwinism, and what can be learned from this about the nature of technology diffusion?*

For the case study analysis, we make use of the System-Network-Agent approach developed by Chiong Meza (2012), but in an adapted and simplified way. In this approach, a distinction is made between ***three conceptual levels***: the system level, the network level, and the agent level. In the system level, a useful concept is the 'drastic event', i.e. a 'compelling force that may speed up a system transition'. Networks have been described to represent interaction mechanisms between agents (actors), and also a distinction has been made between different fields that resemble the societal domains given above. On the agent level, different actor roles are distinguished between: government, producers, facilitators, consumers, infrastructure intermediaries, research organisations, and interest groups (Chiong Meza, 2012).
In this work, we adopt the distinction between the three conceptual levels, including the concepts of drastic events and actor roles. The network level we consider to be the level in which actor interaction and the co-evolution of societal domains take place, which stems from individual behaviour on the agent level.

Because technology diffusion is a process that results from the investment decisions of individual companies in an industrial sector, understanding the decision making of enterprises is a key step towards the understanding of technology diffusion. To structure the analysis of individual behaviour regarding technology investment and use, we have made a conceptualization of ***company decision making***. This is illustrated in Figure 1.

[1] Not all co-evolutionary mechanisms are necessarily mechanisms found in nature, however.

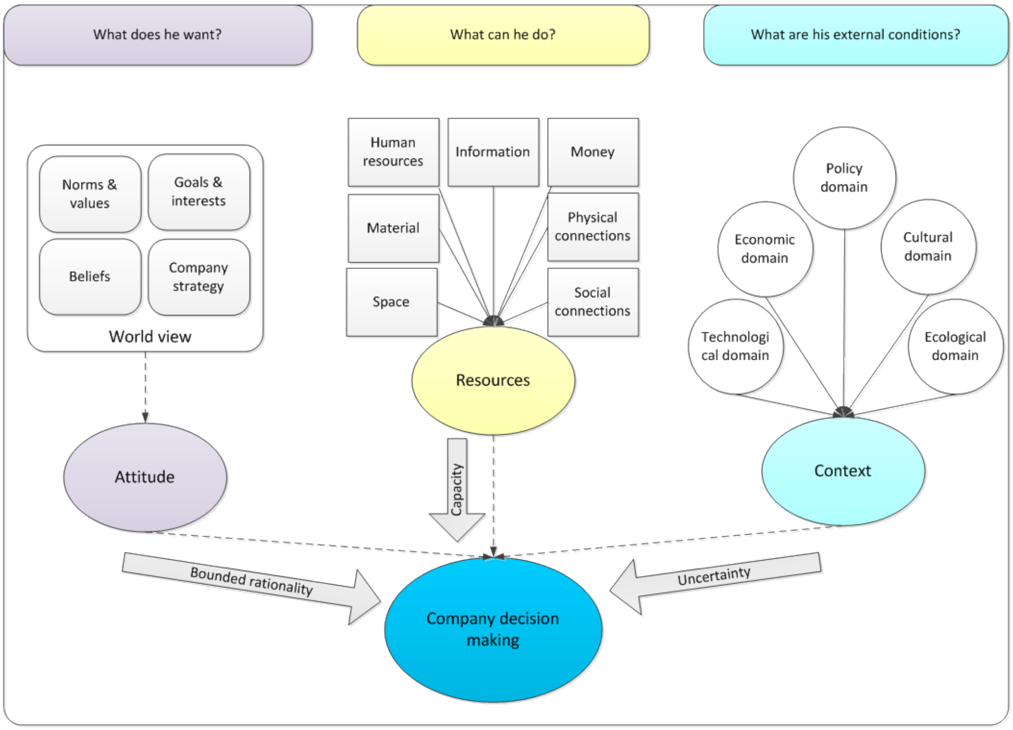

Figure 1. Conceptualization of company decision making

Individual decisions are influenced by three elements: attitude, resources and context. *Resources* are the means that the company has to deploy business activities (invest, operate, trade, etc.). Important resources are money, material (equipment and feedstock), human resources, space, information, physical connections (e.g., network connections), and social connections (relationships with other actors). *Attitude* includes the wide range of values, ideas and thoughts the company has: Norms and values, goals and interests, beliefs, and company strategies. *Context* encompasses the socio-technical system of which the company is a part, which influences the number, nature and impact of choices he can make. Here, the distinction between the different societal domains is useful as well, because they represent different (but interrelated) aspects that companies consider in their decision making.

The resources and the context together delineate the 'decision space' of the company, whereas the attitude stands on the basis of company decision making. This decision making often takes place under uncertainty, which companies must deal with in some way. Furthermore, companies (like all human actors) have bounded rationality (Simon, 1956): Because of cognitive limitations they behave rationally only to some degree.

In short, understanding of company decision making requires knowledge about resources, context and attitude of individual companies. This concept of company decision making is added to the agent level that is part of the three conceptual levels (see above).

3. Methodology

For the historical case study, we have carried out a literature study, including both academic and sectorial literature. Next to that, we have conducted semi-structured interviews with stakeholder experts. Five interviews with experts from stakeholders in the Dutch greenhouse sector have been conducted, i.e. from WUR Glastuinbouw (a knowledge institute), Energy Matters (a lobby organization for CHP), LTO Noord Glaskracht (the main greenhouse sector association), AgroEnergy (an energy service provider oriented to the greenhouse sector), and GE Jenbacher NL (a CHP unit supplier). Also, we conducted interviews with five greenhouse growers: two tomato growers (a large one and a small one), an eggplant grower, an orchid grower, and a rose grower. These growers are, just like many hundreds of other greenhouse companies, located in the Westland area. See Figure 2.

Semi-structured interviews are interviews where the interviewer asks open questions, using keywords, and where he asks new questions in response to the answers to gain more insights (Leech, 2002). This generates for more detailed and rich answers, while interviewees are not steered too much in a certain direction. We have made use of a short list of key questions that we have posed to each grower. See Box I.

In the case study analysis in Section 4, and in the presentation of gained insights in Section 5, we have included some quotes from the interviews with the greenhouse growers to support our findings. These quotes are written in italic.

Figure 2. Satellite photo of the Westland area (website Google Maps, 2012)

Closed questions

- How large is your greenhouse company?
- What type of crops do you grow?
- How much electricity, heat and CO_2 do you need?
- How large is your CHP installation?
- What are the technical specifications of the CHP installation?
- When did you invest in this installation?
- How large is the heat buffer (if any?)
- Does the installation include a flue gas cleaner?
- Do you deliver electricity to the grid?
- Do you deliver heat to neighbours?
- What is the operation time of the CHP unit?

Keyword questions about investment decision

- About ***company resources****:*
    - Was CHP a *suitable* option considering required *inputs* for production?
    - Did you have the *capital* for the investment?
    - Did you have the required *knowledge*?
    - Did you have enough *physical space*?
    - Did you have the required *gas and electricity network connections*?
    - Did you have any required *connections with organisations*?
- About ***company attitude****:*
    - Which *company objectives* were important regarding the investment decision?
    - What was your *original view on CHP*?
    - How *sustainable* do you consider yourself to be?
    - How *innovative* do you consider yourself to be?
    - What is your *perception of sustainability and innovation*, and did this play a role in the investment decision?
    - What is your *perception of uncertainty and risks*, and did this play a role?
- About ***context****:*
    - What role did the *availability of technology* play?
    - What role did the market situation in the *greenhouse horticulture* play?
    - What role did the market situation in the *energy sector* play?
    - What role did the market situation in the *CHP unit supply sector* play?
    - What role did *public opinion* play?
    - What role did the *relationships with other stakeholders* play?
    - What role did *government policy* play?
- *How long* did it take you to reach a *final decision* on whether to invest in CHP?
- What *information* did you gather to make the final decision?
- Where did you *gather* this information?
- To what extent have you made use of *calculations, external opinions, argumentation,* and *intuition?*

Keyword questions about operational decisions

- Which *operational strategies* do you apply, i.e. for CHP control and energy trading?
- To what extent have these operational strategies been considered in the CHP *investment decision*?
- In what way did you *develop* your operational strategies throughout the years, and for what reasons? What role did *learning* play in this?

Box I: Main questions posed to the growers in semi-structured interviews

4. Historical case study

At the end of the 1970s, CHP was already a well-known technology to large industrial companies in the Netherlands, who had a high demand for heat and electricity, and the knowledge and capital to adopt combined heat and power (CHP) technology. Besides, between 1974 and 1982, the electricity price had doubled, increasing the economic attractiveness of investment in CHP. In the 1980s and 1990s, subsidies from the Dutch government for CHP, in combination with the emergence of a stable spark spread, i.e. the difference between the natural gas price and the electricity price, drove the adoption of CHP facilities in Dutch industries further upward. A temporary moratorium on the construction of CHP units was introduced in 1994, as a result of an explosive diffusion of CHP, depleting subsidy funds and risking large electricity surpluses in the electricity market**.** This moratorium gave an extra impulse to the growth of small-scale CHP in the horticulture and services sector **(**Hekkert, Harmsen and de Jong, 2007).

In the Dutch greenhouse sector, CHP units were installed in the 1980s and 1990s by flower growers with a high electricity demand for illumination in their greenhouses. Probably imitating the use of these units in other industries, and benefiting from the CHP support schemes, they installed CHP units dimensioned to provide the electricity demand of their companies. In addition, the produced heat could be utilized as well. These units were often not connected to the electricity grid, and allowed growers to significantly reduce their energy bill. These form a first 'greenhouse CHP type'.

The Electricity Act of 1989 made possible the development of joint ventures between distribution companies and industries. These were initiated by distribution companies, who installed a CHP unit at the growers' company site, and sold the heat to the grower at a discount. The distribution company owned and operated the CHP unit. This is a second greenhouse CHP type. These joint ventures were attractive to growers: "*Westland Energie was looking for large companies to sell heat to. For us, it was zero investment, we just needed to provide the space. They arranged the CHP, and we got the heat with a discount.*" In the course of the 2000s, however, these joint ventures became less profitable for energy companies, as a result of which this greenhouse CHP type diminished from 500 MW_{el} in 2000, to about 100 MW_{el} in 2011 (van der Velden and Smit, 2011).

In 2002, the electricity market was opened up for the greenhouse sector. After the adaptation of a General Measure of Governance (AMVB) by the Dutch government that prohibited CHP instalment by growers without an environmental permit, greenhouse companies were allowed to invest in CHP units that were used to not only produce heat, electricity and CO_2 for their own crop cultivation, but also to inject electricity into the grid after selling it in the electricity market. With this, greenhouse companies also became electricity producers. To sell more electricity, CHP units were sometimes over-dimensioned, i.e. larger than the average 0.5 MW_{el} per hectare needed for crop cultivation. To be able to produce and sell electricity at the highest prices, large heat buffers were also being installed, as growers found out that CHP operation during the day and storing heat for use at night was a profitable operational strategy. The utilization of the CO_2 from the CHP facility required a flue gas cleaner, but the quality of that CO_2 was not always found sufficient, whereas the introduction of the OCAP pipeline from 2005 onward provided a better alternative for CO_2 supply[2]. This is a third 'greenhouse CHP type'.

Due to the proven high profitability of this third type of greenhouse CHP, the total installed capacity of CHP in the Dutch greenhouse sector has grown rapidly and immensely in the period 2003 to 2009, from 1,000 MW_{el} to 3,000 MW_{el}. See Figure 3. Growers were able to earn back the CHP investment in three to four years. An event advertising the economic potential of the CHP unit for growers was the 'code red' situation in the Dutch power sector during one week in the summer of 2003. In this week, power prices above 1,000 euro/MWh occurred (website Energie.nl, 2003), allowing some tomato growers to make enormous profits by selling all energy to the market and releasing excess heat into open air. But more structural examples of profitability were provided by early adopters like tomato grower cooperative Prominent, where about fifteen growers placed a group order for CHP units as early as 2004. This occurred after the investment by Prominent in a single CHP unit in 2003, for the purpose of illumination of crops in one company (in order to test the possibilities for growing tomatoes in the winter months as well). As mentioned by an interviewed tomato grower from Prominent: "*First we started with lighting there, but then we found out that with delivering back to the grid you could obtain a large reduction of energy costs.*" Thus, the greenhouse sector quickly learned about the true potential of CHP, and the transition really took off. Furthermore, some environmental investment subsidies, and a feed-in tariff (which was aborted in 2006), contributed to this rapid uptake as well.

By 2006, not one new greenhouse was built without CHP installation (Roza, 2006), and the greenhouse sector even became a net supplier of electricity. In 2008, almost 11 TWh (about 10%) of the total Dutch electricity demand was produced in the greenhouse sector. This indicates that a significant amount of power from greenhouse CHP units was sold and fed into the grid at that time, utilizing the business opportunities in the electricity market. Indeed, 53% of the electricity generated by CHP units in the greenhouse sector was injected into the grid in 2005. By 2010, this had risen to 64% (van der Velden and Smit, 2009). In 2010, for 62% of the total greenhouse cultivation area (ca. 6,400 ha) a CHP installation was used (van der Velden and Smit, 2009; van der Velden and Smit, 2011), covering most of the 'warm cultivation' in the country. This large and rapid diffusion can be rightly called a transition.

The supportive governmental policy regarding CHP in the Dutch industrial sector has been motivated mainly by energy efficiency considerations. This is reflected by the drawing of sustainability targets in the sectorial Convenant Schone en Zuinige Agrosectoren. However, this covenant did not stipulate any obligations for individual growers; it was more a common set of goals to be pursued by the sector as a whole. Therefore, the reasons for growers to invest in CHP facilities have been purely economic. It is the very attractive economic benefits that drove the growing CHP adoption, to which the subsidies from the government only contributed to a limited degree. The main factor was the favourable 'spark spread', the difference between the electricity price and the gas price, which shows the profit to be gained by growers from producing electricity with a CHP unit and selling to the market. But it

[2] The OCAP pipeline delivers CO_2 that is produced in industrial processes in the Rotterdam harbour area to greenhouses in the Westland area. The company OCAP ('Organic Carbondioxide for Assimilation of Plants') originates from an idea by a then energy company in the nineties. Nowadays, OCAP delivers over 400 kilotonnes of CO_2 per year to about 580 greenhouse horticulture companies (website OCAP, 2012).

also indicates the energy cost reductions achieved by substituting electricity purchase with self-generated electricity, as the spark spread is reflected in the Dutch electricity price[3].

Nevertheless, this economically driven CHP diffusion has had a very positive effect on the environmental performance of the Dutch greenhouse sector. At the end of 2010, the greenhouse sector used 53% less primary fuel per unit of product compared to 1990. This was also caused by improvement of the cultivation processes, but growers with a CHP were responsible for 20 percent points of the primary fuel use reduction, i.e. a 38% contribution. Next, the total CO_2 emission reduction of the sector reached 3.2 Mton compared to the 1990 level, of which 2.4 Mton (75%) from CHP deployment[4] (van der Velden and Smit, 2011). The large environmental contribution of CHP results from the high energy efficiency that can be realized with CHP: Over 90% of the chemical energy of natural gas is converted to electricity and heat, which is stored and utilized within the company, or distributed to neighbours. Compared to electricity withdrawal from the grid, which is generated by power plants with less than 50% electrical efficiency and is subject to transport losses of up to 10%, this means a big improvement in energy efficiency.

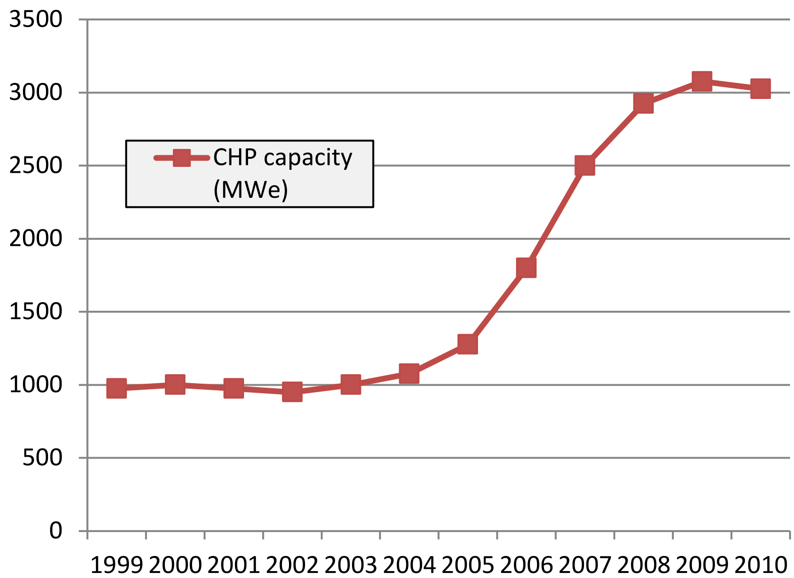

Figure 3. Total electrical CHP capacity in the Dutch greenhouse horticulture (van der Velden and Smit, 2011)

In 2010, however, the rapid diffusion of CHP in the greenhouse sector came to a halt. The profitability (spark spread) of CHP units in greenhouses had dropped to almost zero (Vermeulen, 2011). For an important part this was caused by developments in the electricity market. The expansion of electricity production capacity in the Netherlands, an increasing amount of interconnection capacity, and further electricity market integration have reduced the profits of greenhouse farmers from selling electricity to the grid (Platform Kas als Energiebron, 2011; Energy Matters, 2011). At the same time, the low spark spread has made self-generation of electricity compared to purchasing from the market less beneficial, and the pay-out time has increased significantly. This has made the investment in CHP in the year 2012 a much more uncertain business case.

[3] Natural gas-fired power production in the Netherlands takes up a high share in the production mix, and offers from gas-fired power plants are often price-defining.
[4] The CO_2 emission related to the sold electricity is not incorporated in this.

5. Gained insights

5.1 Observed phenomena

Observed phenomena in the case study 'CHP diffusion in Dutch greenhouses' include both static phenomena and dynamic phenomena. The static phenomena are often features of greenhouse sector or CHP technology, while the dynamic phenomena are often developments of these features resulting from their interaction. The phenomena are categorized based on the three conceptual levels (see Section 2).

System level

Drastic events

- The opening of the energy market for the greenhouse sector in 2002, which enabled greenhouse companies to become an electricity market player, and sell electricity from CHP operation in the electricity market.
- Huge profits of a large tomato grower during code red situation in Dutch power system in 2003, which indicated the economic opportunities of selling electricity from CHP operation. Due to this event, all growers came to know about the option of CHP: "*Whether the example of that tomato grower spread like wildfire? Absolutely, everyone knew about it. In ten days he earned one million euros.*".

Network level

Actor network

- *Government*: The Dutch national government is the relevant governmental actor in this case study. It has supported CHP diffusion with various subsidy schemes, and has stipulated environmental targets for the greenhouse sector through covenants.
- *Producer*: From the perspective of the central actor of the greenhouse company (grower), energy supply companies form a relevant group of actors. Growers purchase electricity and gas for their electricity, heat and CO_2 needs. If a CHP unit is installed, a grower still buys gas, and electricity at times when it is cheaper than self-generation. Another relevant producer is the CHP unit supplier.
- *Trader*: Regarding the selling of self-generated electricity by growers, the energy broker is a relevant actor. As growers cannot trade energy without acquiring some authorization, this selling is often facilitated by traders. Alternatively, growers could sell directly to an energy supply company or on the power exchange.
- *Consumer*: The role of the consumer is in this case study played by the greenhouse company, i.e. the central actor. The greenhouse grower consumes energy and CO_2 for its crop cultivation, and 'consumes' CHP units to reduce energy costs and increase profits.
- *Infrastructure intermediary*: Pertaining to the actor role of the infrastructure intermediary, the distribution system operators of the gas network and the electricity network are relevant actors. CHP units must be connected the gas and electricity grid, for which the distribution system operators are responsible.
- *Research organisation*: In this case study, research organisations appear to not have played a significant role.
- *Facilitator*: Four main facilitators play a role regarding CHP investment by growers. Banks have provided loans and leasing companies offered leasing constructions for

financing of the investments. Greenhouse sector cooperatives and advisory companies have facilitated CHP information gathering, investment planning, and actual investments. Advisory companies could give more specific advice, but cooperatives could enable joint investment projects.

- *Interest group*: Three interest groups have played a small role. The Productschap Tuinbouw (PT) has been of least importance. Supported by the government, it financed research and pilots on more sustainable greenhouses, and therefore also CHP technology. LTO Glaskracht Noord defends the interests of greenhouse companies, and has both informed growers about CHP and lobbied for CHP subsidies. COGEN Projects (now Energy Matters) has also lobbied for CHP subsidies, and for appropriate gas engine emission regulations.

The actors that have played a major role in the CHP diffusion in the greenhouse sector are the national government, the greenhouse companies, and the greenhouse sector cooperatives. Actors with a moderate role are the CHP installation providers, the energy supply companies, the energy brokers, the distribution system operators, leasing companies, and the banks. Actors with a minor role are the advisory companies, Productschap Tuinbouw, LTO Glaskracht Noord, and COGEN Projects. We must note that all actors indicated to have played a moderate role did have 'blocking power', i.e. owned indispensable resources to realize CHP investment, but no problems were anticipated or have emerged with regard to their role in the diffusion process. Next to these actors, the national government also had blocking power, but in actuality it was a dedicated actor enabling and supporting the CHP diffusion.

Societal domains

<u>Technology:</u>

- CHP was a well-known technology for generating heat and power in Dutch industries already in the seventies.
- In the nineties CHP became well-established in the greenhouse sector in illuminated cultivation ('greenhouse CHP type 1'), and owned by energy companies ('greenhouse CHP type 2').
- For illuminated cultivation (flowers), the CHP unit is used first and foremost to self-generate electricity (greenhouse CHP type 1). For warm cultivation (vegetables), the CHP unit is used first and foremost to produce heat (greenhouse CHP type 3).
- CHP units for illuminated cultivation (greenhouse CHP type 1) were often not connected to the electricity grid before liberalization, but this has changed afterwards. Heat was typically provided to neighbouring greenhouse companies with warm cultivation.
- Multiple CHP generation technologies exist, but the gas engine has always been the technology of choice, due to its favourable costs, efficiency and operating conditions.
- A CHP unit is usually accompanied by a heat buffer, which introduces the operational flexibility to generate power at times of low heat use or high electricity prices, store heat, and use this heat later.
- In combination with an overdimensioned CHP unit, operational flexibility becomes even higher: "*If you design your CHP at a half MW per ha., you always must operate. With a large CHP you have some more possibilities to play with.*"

- To extract CO_2 from the flue gas for utilization in the greenhouse, a flue gas cleaner can be added to the CHP installation. The quality of this CO_2 is however lower than from the boiler and from the OCAP pipeline (see below), i.e. contains more ethylene, which may affect crops. Furthermore, using an external CO_2 source also provides more flexibility of the operation of the CHP unit.
- The good match between the demand for electricity, heat and CO_2 from greenhouses, and the supply of electricity, heat and CO_2 by CHP units, made CHP installations a well-fitting feedstock providing system for greenhouse companies. For vegetable growers, the higher CO_2:heat ratio of the CHP unit compared to the boiler benefited the growth of crops: "*Per volume of heat you then suddenly have two times as much CO_2, and that we could utilize well*".
- An important alternative source of CO_2 in the Westland is the OCAP pipeline that became operational in 2005. This provided a higher quality CO_2 compared to CO_2 obtained from the CHP unit with a flue gas cleaner: "*We have quite a sensitive cultivation with eggplants, which is quite a sensitive crop. CO_2 from the CHP is not so clean as that from the boiler. CHP-CO_2 contains some substances, like ethylene, in low concentrations, that you really do not want to have in your glasshouse. Whether that cannot be removed with a flue gas cleaner? No, a small concentration always remains. So that is why I chose for OCAP, you just know you get pure CO_2.*"
- Alternative heat provision technologies for greenhouse growers include solar boilers, heat-cold storage, heat pumps, and geothermal energy. However, these generally provided less useful output (no CO_2 and electricity, lower efficiency) and were often higher in costs and less proven. Only a small minority invested in this, and often not instead of, but in addition to, a CHP unit.
- An alternative technological concept for saving on energy costs, the 'closed glasshouse' that was studied in theory and practice around 2003 as well (Raaphorst et al., 2006), appeared to bring much lower economic gains: "*The return of the CHP was a lot larger than that of the closed glasshouse. We contributed to that as well, but the return of that was not that large.*"
- An alternative fuel for CHP units is biomass. By 2009, only three growers had invested in biomass-fired CHP (van der Velden and Smit, 2010). This is probably caused by multiple disadvantages of biomass compared to natural gas: its lower availability, the higher purchase price per unit of energy, the varying liquid content, net heating value, and particle size, and the need for pre-processing of biomass. Furthermore, it has never been an established option in the Netherlands.

Economics:

- The transition period was in general characterized by high electricity prices, low gas prices, and therefore high 'spark spreads'. The high profitability and low return on investment (ROI) period were due to these high spark spreads. This was the main driver for growers to invest in CHP: "*It does not matter how high the electricity price is, it is all about the spark spread.*".
- The costs of a CHP installation were in the order of 600,000 euro/ MW_{el}. The ROI period was on average 3-4 years during the transition period 2003-2009.
- It was not difficult to get a loan or leasing construction at the bank. A leasing constructing was common, as it was less of a financial burden in the short term: "*With that lease construction, you immediately grabbed that profit. For us, that was better on the shorter term, otherwise we would have had very high start-up costs,*

while now it was nicely spread out over the entire period. ... Thanks to that, we had the EIA [Energie Investeringsaftrek, a subsidy for investment in energy-efficient energy systems] 5-6 years earlier.". Other growers preferred to take a loan to finance their CHP investment, which was likely cheaper in the long run[5].

- Recently, due to the economic crisis, it has become much more difficult for greenhouse companies to get a loan from the bank for e.g. CHP investment or a harvest credit (to cover yearly investments in plants): "*Whether I had to show an investment plan? Yes, our return. What the cost picture of the energy looked like before and after the investment. That went very smoothly, yes, it was not a problem. Now it is very dramatic, yes, and it indeed comes down to it that the bank determines whether he wants to maintain your company or not.*
- From 2002 onward, growers could sell self-generated electricity in the electricity market, which created a large energy cost reduction, or even a profit for their company. Because the company profit from selling electricity turned out to be significant, the operational strategy of growers with a CHP unit shifted quickly from heat demand-following to electricity price-following.
- This shift in operational strategy has generally led to more overdimensioning of CHP units, larger heat buffers, a growing share of self-generated electricity being sold instead of used in the company, and more short-term energy trading.
- The high attractiveness of CHP investment caused a steep increase in demand for CHP units, which at some point (2005) CHP suppliers could not cope with, importantly due to a lack of skilled installation mechanics (interview GE Jenbacher NL). Also, the connection of the installations to the energy networks by the distribution network operators required time, which has probably led to more delays in actual installation: "*Some CHPs could be connected to the grid immediately, others could not. ... Most times, they managed to do this within a couple of months.*".
- The attractiveness of CHP units for growers with illuminated cultivation (greenhouse CHP type 1), who had a high electricity demand, was also based on electricity and gas prices. Self-generation saved paying transport costs and energy tax (for which CHP-gas was exempted): "*If I calculate how much the transport costs are and what the power costs, then it's better to generate the power myself, because I do not have any transport costs then.*". The selling of excess heat has for those growers become a more important economic precondition for investment over the years, as the spark spread dropped.
- The attractiveness of utility-owned CHP units (greenhouse CHP type 2) for energy companies decreased in the transition period, resulting in a large reduction of this type of CHP unit, a trend opposite to that of the grower-owned CHP unit for warm cultivation (greenhouse CHP type 3). "*The energy companies even dismantled their CHPs at the time we started to install them. Those companies did that because the revenues were bad for a couple of years.*"
- Over the years, the profitability and return on investment period for CHP units in greenhouses have dropped down to a point at which it has become an uncertain business case. Partly, this is caused by the very development of CHP diffusion, because this has contributed to higher competition and thus lower prices in the

[5] Among the interviewed growers, two obtained a loan and three went for a leasing construction to finance their investment in a CHP installation.

electricity market. Other factors are a general increase in electricity production in the Netherlands, increased import capacity and international power trade, and a resulting decoupling of power prices from gas prices, deteriorating the spark spread.

- The lower spark spread has brought tomato growers with CHP units to invest in illumination, utilizing self-generated electricity to enhance crop production: "*The last year a lot has been invested in lighting in the tomato world. Because grid delivery is no longer interesting. Because tomato is a food product there is GMO-subsidies on it, and if you get 50% subsidy for your lamps, it is easy to calculate this through [obtain a positive business case].*"[6].
- The availability of cheap CO_2 from the OCAP pipeline as an alternative CO_2 source has brought most growers who could connect to this pipeline to not invest in a flue gas cleaner as part of their CHP installation.

Policy:

- In the seventies and eighties, the national government has stimulated CHP with various measures. This has contributed to the uptake of CHP technology by Dutch industries.
- The Electricity Act of 1989 enabled the establishment of joint ventures between energy distribution companies and industries, resulting in the introduction of greenhouse CHP type 2 in the greenhouse sector, in which the energy company owned and operated the CHP unit located at a greenhouse company, and sold heat at a discount to that company.
- Electricity market liberalization, in particular the opening of the electricity market for the greenhouse sector in 2002, made it possible for greenhouse companies to become electricity producers, and sell energy in the electricity market. In addition, the Dutch government adapted a General Measure of Governance that prohibited the installation of CHP units by growers without environmental permit.
- In the transition period 2003-2009, various temporary subsidy schemes have been deployed by the national government to stimulate CHP in the Dutch industries, including a feed-in tariff for CHP electricity, an exemption of CHP gas from energy tax, and multiple investment subsidies for which CHP units were eligible. The feed-in tariff was halted (in 2006) as soon as was clear that it was not needed anymore to make CHP investment profitable. These subsidies did support the transition, but were not decisive: "*If that [subsidies] was an important precondition for my investment? It made it more interesting.*".
- Stimulation of CHP in the seventies and eighties was already motivated by environmental and energy efficiency considerations. Specific environmental targets for the greenhouse sector were incorporated in sector covenant with the aim to improve environmental performance. This covenant did not play a role in the investment decisions by growers, but has probably been a reason for the government to maintain subsidy schemes for industrial CHP, noticing its high contribution (potential) to energy efficiency targets.

[6] This is an example of a technological development that was influenced by an economic development, i.e. an example of interplay between developments in different societal domains. A lot more interplays between domains can be easily derived from the observed phenomena in this case study, which confirms the relevance of the concept of co-evolution of societal domains for technology diffusion processes. In order not to create unnecessary repetition, we have not listed examples of co-evolution from the case study explicitly.

Culture:

- The governmental culture can be labelled as environmentally driven and innovation-stimulating, which has led to the stimulation of energy efficient technologies in industry in general, and industrial CHP in specific.
- The sectorial culture of the greenhouse sector can be labelled as competitive, cooperative, and cost-driven. As vegetables, pot plants and flowers are quite homogeneous products competition is based on costs, while supermarkets have squeezed out the profit margins on these products. Despite the intense competition, greenhouse companies do cooperate to lobby for their common interest, and they share information about new technologies.
- Greenhouse companies are very entrepreneurial and hard-working, which is probably fuelled by the fierce competition in the vegetables and flowers sector. They are open to new technologies (innovative) and are not afraid to adopt these relatively quickly, for the sake of competitiveness, but also because they like to introduce and use new concepts in their daily business (Schrauwen, 2012).
- Greenhouse companies are often family companies: They have been transferred from father to son, and often a lot of family members work in them (Schrauwen, 2012). This probably creates a lot of trust and cohesion in their work, and motivates to stay in business.
- The corporate strategy of greenhouse growers generally focuses on maximizing the production of crops (per square meter) and minimizing the cost price (per kilogram of product), in order to maximize profitability. According to the growers, the introduction of CHP installation has not altered this, but they admit that the profits from selling electricity formed a significant part of their profitability in the transition period. Indeed, we have found that operational strategies have shifted in support of the energy business, but that cultivation strategies did not need to change thanks to the operational flexibility of the CHP installation. However, different growers make different decisions regarding focus on cultivation vis-à-vis focus on energy: "*I have consciously made the choice: my CHP is only there to improve my yield. I have to earn money with the garden, with the crops, and not with the energy trade. That is my strategy.*".

Ecology:

- CHP installations highly improve the energy efficiency of greenhouse companies, but this has not been a reason for growers to adopt CHP technology. The intense competition in the crop markets had caused greenhouse companies to focus on the reduction of production costs. Besides, they did not devote much attention to marketing, and 'sustainable vegetables' were considered not marketable (Schrauwen, 2012).
- Interestingly, the diffusion of CHP can be considered environmentally beneficial and innovative on the one hand, but it (temporarily) decreased the potential for more sustainable and innovative energy technologies in the greenhouse sector on the other hand. Thus, it slowed down the development of such technologies (van der Velden and Smit, 2011).

Agent level

Context of greenhouse companies

- Regarding technology, CHP is proven technology, and its outputs fit the needs of the greenhouse company.
- Regarding economy, the high spark spread has led to a high economic attractiveness of CHP investment: high profitability and a low ROI period.
- Regarding culture, information spreading and cooperation within the sector has aided in CHP adoption, while the competitive nature brought companies to quickly follow the CHP investment plans of their competitors and colleagues.
- Regarding policy, the Dutch government has made possible the development the 'third greenhouse CHP type' by opening up the energy market for the greenhouse sector. Also, it supported CHP investment by means of various subsidy schemes, which made investment in CHP even more attractive.
- Regarding ecology, the environmental benefit of high energy efficiency was not an advantage of CHP technology considered by growers. They might have considered the contribution to the sectorial environmental targets as an additional advantage, but this is not something the interviewed growers have indicated.

Resources of greenhouse companies

- The financing of the investment in a CHP unit required greenhouse companies to take a loan from the bank, or arrange a leasing construction with a leasing company.
- The CHP unit requires some physical space on the greenhouse company compound. This generally did not pose a problem.
- A CHP unit had to be connected to the gas network and electricity network, but at least for the interviewed growers the existing connections had enough capacity to install the CHP unit. However, a transformer had to be invested in (to convert the voltage of generated power). This was considered a part of the total CHP installation investment.
- The joint ventures between energy companies and greenhouse growers after 1989 resulting in greenhouse CHP units of type 2 at the greenhouse company compounds has made the greenhouse companies more familiar with this technology, contributing to the consideration of CHP technology investment. However, growers generally did not buy over the CHP units owned by the energy companies, but rather invested in a newer and more efficient unit.
- With regard to information gathering it was useful to have some connections with other growers, but this certainly was present. For some growers it was quite useful to look at and discuss with their neighbours, some contracted an advising company, and some both discussed and invested in CHP with other growers. "*Whether I also looked at other growers' investment and use of CHP? Yes, and also at the neighbour, he had one early on, and I have learned a lot from that too. If I talked a lot to him? Yes. I just walked in, and said: 'Can I just look how that works?' Then he also showed me on his computer how purchasing and selling is done. I learned a lot from that, yes. Also about: how much do you save, I think that is the most important.*".

Attitude of greenhouse companies

- As already mentioned above, greenhouse companies can be characterized as entrepreneurial, competitive, cost-driven, cooperative, and innovative. Of these, 'cooperative' appears to be at odds with 'competitive', but the cooperation takes place on a sectorial level (lobbying), and in cooperatives (shared activities to reduce costs and increase revenues). Detailed company information is of course not disclosed. Regarding new technologies, however, companies are open, and willing to inform others.

- Given these both characteristics of greenhouse companies, it comes to no surprise that CHP technology has been embraced by the sector, and that the diffusion of CHP units in the sector boomed in just several years. It was not that growers were not open to other environment-friendly technologies than CHP, but financial calculations and practice (pilots and first adopters) pointed to clearly higher economic benefits for companies with a CHP installation.
- Some growers have been more reserved towards CHP than others (were more risk-averse): "*Why I invested in CHP only in 2007? Really to see which way the cat jumps, which way the energy is heading, because it really is a gigantic investment to install such a machine. ... . I thought that it [the return on investment] was a bit too uncertain still [before that]*.".
- The high energy efficiency of CHP has not been a (significant) reason for investment: "*The grower is not sustainable by nature. The own wallet. That is not sustainable, that is a smart calculation.*"
- Many growers consider the energy trading after liberalization as a complicated business compared to crop cultivation, but most growers have grown accustomed to the new opportunities provided by the installed CHP unit, and responded to them. Some less crop-oriented growers have over-dimensioned to be able to sell more electricity. Much electricity is sold on the day-ahead market, which means some risk on sold quantities and thus on CHP operation hours and heat production, but generates higher revenues due to higher electricity selling prices. One of the interviewed growers sells most power in the balancing market, which is characterized by even higher prices and risks: "*If you look at the APX[7] prices, you've got only 61-62 euro. If you run at imbalance, by taking that risk, you might make 80-90 euro on average.*". The applied energy trading strategy depends on the risk attitude: "*That is more or less the game you play: Do you want to take a risk, actually a sort of gambling, or do you play safe, but with a lower return?"*.

<u>*Decision making by greenhouse companies*</u>

- Regarding investment in new technology, greenhouse growers are rapid decision-makers. First of all, the fierce competition drives growers to invest in new technology to reduce variable costs and improve competitiveness. Secondly, the greenhouse companies typically have a small hierarchical structure, where the company owner can take the investment decision on his own. Thirdly, they are open to new uncertain innovations, and once they have made up their mind about following up an investment plan they will carry it out with conviction.
- The open and assertive attitude to innovation has led growers to discuss among colleagues the possibilities of CHP, leading to quick and informed investment decisions, as the expert from Jenbacher explained. One grower declared: "*We appointed a commission for that [joint CHP investment]. With six people we have developed this in every detail, and studied it all.*"
- Regarding CHP units, the investment decision was easy and quick, because of the clearly positive business case. The details of the investment plan were also not

[7] APX stands for Amsterdam Power Exchange.

difficult: it was easy to obtain financing, physical space and network capacity was available, there was only one commonly used CHP generation technology for the relevant capacity range, and the typical size was 0.5 MW_{el} per hectare cultivation area. "*Whether the investment decision for that first CHP was made quickly? That is simply a matter of calculating. I know how much electricity I need, I know what it costs if I buy from the grid, I know how much it costs to buy a CHP, so that can be completed within 5 minutes. You do not have to think long about that. I would have earned it back within three years, so then it is of course quickly installed.*"

- By 2012, investment in CHP has become a much more difficult business case, and requires a better estimation of future developments in especially the energy market.
- The operation of CHP was said to be in service of cultivation, but the heat buffer provides a lot of operational flexibility, which was thankfully exploited by the growers. The energy trading practices (whether to purchase gas and sell electricity in long-term or short-term markets) have developed as a result of learning-by-doing, but it remains a bit based on intuition, as energy prices are erratic and difficult to forecast. The amount of effort that greenhouse companies put into the optimization of energy trading depends on their money budget and available time: "*A good control system pays off itself three times. That is why large companies put a guy on that. As a small company I cannot do that, which is why the system needs to function well and automatic.*"

5.2 Key drivers

Based on the observed phenomena described above, we have identified five key drivers of the rapid diffusion of CHP installations in the Dutch greenhouse sector in the period 2003-2009. These are the following:

The *opening of the energy market* for the greenhouse sector in 2002 has enabled greenhouse companies to become an electricity market player, and sell electricity from CHP operation in the electricity market. By this, the 'third' greenhouse CHP type (ownership and operation by growers, and selling of electricity) was introduced, which was quickly discovered as a highly profitable business case for companies with warm cultivation.

The *high spark spread*, i.e. the large difference between the electricity price and the natural gas price, made the investment in a CHP installation very profitable, with a projected return on investment period of three to four years.

The *compatibility of CHP output with greenhouse demand* made the CHP unit a suitable investment in terms of generated inputs: Not only were the three products generated by CHP operation, i.e. the electricity, heat and CO_2, all needed inputs for the cultivation process, but also did the amounts and proportions of these products fit the greenhouse demand.

The *flexibility provided by the heat buffer* was a highly useful feature of the CHP installation that further improved the goodness of fit of CHP outputs with greenhouse demand, and enabled even higher profits from selling electricity, by providing the option to generate at hours of high power prices while storing the excess heat for later use.

Finally, the greenhouse *sector culture* was one that could be defined as both *cooperative and competitive*, which stimulated the adoption of CHP technology. The high competitiveness brought greenhouse companies to quickly follow other companies for which CHP operation was delivering a significant energy cost reduction, while this did not stop companies to inform each other of the benefits of CHP investment and operation, which fitted in the cooperative practices in the sector.

An evaluation of these five key drivers is shown in Table I. We have identified related societal domains, sectors (scope), and the origins of the drivers, i.e. how the drivers came into existence. A first insight from this is that all societal domains play a role in this set of drivers, showing the transition of CHP diffusion in Dutch greenhouses was multi-dimensional, and indicating that this transition indeed has been a result of the co-evolution of societal domains. Secondly, developments in three sectors have played a role in the transition: the greenhouse sector, the CHP supply sector, and the energy sector, so also the interplay between developments in these sectors have contributed to this transition. Finally, the origins of the key drivers show that some drivers are the result of much more general developments (opening energy market, cooperative and competitive culture), that specific combinations of developments in different domains can cause specifically strong drivers (spark spread), and that some drivers are rather characteristics which happen to be favourable for this particular technology diffusion case (compatibility CHP output and greenhouse demand, heat buffer).

Driver	Domain	Scope	Origin
Opening energy market	Policy, economic	Greenhouse sector	National energy market liberalization trend
Spark spread	Economics	Energy sector	National energy demand and supply, price-influencing policy measures
Compatibility CHP output and greenhouse demand	Technology, ecology	Greenhouse sector, CHP supply sector	A 'good match', CHP technology adaptation to industry needs
Heat buffer	Technology	Greenhouse sector, CHP supply sector	Value of heat storage for operational strategies of growers
Cooperative and competitive culture	Culture, economics	Greenhouse sector	Family ties, low margins for growers

Table I. Key drivers of CHP diffusion in the Dutch greenhouse sector in 2003-2009

5.3 Evolutionary mechanisms

In this section, we have listed some evolutionary mechanisms from nature we have identified in the case study 'CHP diffusion in Dutch greenhouses', in order to explore the ability of Universal Darwinism to analyse evolutionary processes in the context of technology diffusion cases, and thereby its usefulness to contribute to the analysis of technology diffusion and the formulation of innovation policy.

General

Four general evolutionary mechanisms are variation, selection, inheritance and adaptation. We identified the following examples of these in the case study, regarding CHP technology.

The mechanism *variation* could show itself in a technology diffusion case in the form of alternative technologies adopted by different individual companies. However, in the case of CHP diffusion in the Dutch greenhouse horticulture, different CHP technologies have hardly been adopted. The conventional gas engine, already widely used in Dutch industries (including the greenhouse sector) before the transition period 2003-2009, was clearly the superior option in terms of technical and economic performance. Moreover, alternative, more sustainable energy systems for greenhouses also were clearly outperformed by the CHP system. Here, the compatibility of the CHP output with greenhouse demand is an important explanatory factor.

Only in different dimensioning and operational strategies we have found some variation, with some growers primarily producing electricity (flower growers) and heat (vegetable growers) for their crops, while others overdimensioned their CHP unit to be able to sell more electricity. This variation can for a part be attributed to differences in growers' attitude towards their primary business and towards risk, but for another part to the particular company size and crop type, and resulting energy and CO_2 needs: "*Roses need to be illuminated much more than orchids, so it [operational strategy] fully depends on how much light and heat you need. I buy 25% of the power, and I produce 75% myself*". Thus, variation in company size, crop type and grower attitude did result in variation on CHP unit size and CHP operation.

The main example of *selection* is the quick adoption of a CHP installation (including a heat buffer) for growers with warm cultivation. After a few years in the transition period, a CHP unit had become a standard for greenhouse companies: "*We determined then that a company with CHP was standard. Indeed, it was strange if you did not have a CHP. It made such a large difference for return. Whether it was also a standard part of a new company? Yes. I think that between 2005 and 2010 not a single new company did not install a CHP.*" For growers with cold cultivation, the selling of heat to neighbours was a way to benefit more from the CHP installations, which were already present before the opening of the energy market. Regarding a flue gas cleaner, the introduction of the OCAP pipeline, which delivered cheap and higher quality CO_2, has brought the majority of the adjacent growers to connect to this pipeline.

The mechanism of *inheritance* has manifested itself by growers copying each other regarding CHP investment and operation, enabled by the open sectorial culture. By 2006, a CHP installation had become even a standard investment option for greenhouse companies, so that we can truly speak of an inherited technology. Nevertheless, the reduction of the spark spread after 2009 has changed this, making the CHP installation an uncertain business case for greenhouse companies.

The last development can be considered an example of *adaptation*: Greenhouse companies have adapted their investment plans to the changes in the energy markets. In general, we can distinguish between cultural, social and individual adaptation. A social adaptation to policies has definitely been identified in the case study: Growers have adapted their CHP investment behaviour as a result of subsidies, but predominantly due to electricity market opening. Before that, in the nineties, the Electricity Act, and the moratorium are examples of general changes in national energy policy that stimulated the investment by energy companies in smaller CHP units located on greenhouse sites. The aforementioned response of growers' CHP investment behaviour to the spark spread, a key driver of CHP adoption, is an example of social adaptation to changes in the economic domain. Individual adaptation has taken place regarding CHP technology. Of course, CHP unit and heat buffer dimensions have been adapted to greenhouse companies' electricity and heat demand. However, at some point the investment plans for extension and building of (new) greenhouse companies also could benefit from taking into account the optimal (most energy efficient) size of a CHP unit, dimensioning the cultivation area to the CHP systems, instead of vice versa. Also, further investment plans in energy systems have naturally taken into account the existence of the CHP unit.

The business operations of the greenhouse companies were adapted as a result of the CHP installation integration as well: "*It was quite a big change, because you have become an energy trader, that is what it boils down to. ... For me as an entrepreneur is has been a gigantic change*". Especially with respect to energy trading, there was a lot to learn, but that was just as well caused by big changes in the energy markets.

An example of individual adaption regarding CHP operation is that the heating strategies in the greenhouse have adapted to electricity market trading practices, which often has led to CHP operation and heating strategies being decided on a day-to-day basis, based on electricity day-ahead prices.

Last, a cultural adaptation resulting from the CHP diffusion has not been found, i.e. the attitude of growers towards technology, innovation and sustainability do not appear to have been changed by the transition.

Specific

We identified examples of the following specific evolutionary mechanisms in the case study, especially with regard to the diffusion of CHP technology[8].

Fertile ground for growth: For large industries in the seventies needing high amounts of heat and power, CHP was a suitable and profitable technology to invest in (also providing additional energy reliability). Also, the technology was known, and the electricity price had risen sharply. Greenhouses in particular provided fertile ground for the CHP technology: Not only heat and power could be utilized, but also CO_2.

Population size / cross-fertilization: CHP was already widely spread in the Netherlands, which increased the likelihood of growers to learn about this technology. Furthermore, energy companies already installed CHP units near greenhouse companies to sell the heat to them, which also contributed to the spreading of ideas for CHP investment.

Familiarity: In nature, animals can become acquainted to a new situation, like other animals or a living environment. Growers could become acquainted to the CHP units installed by energy companies on their company compounds.

Learning: Community learning took place, as the profitability of CHP units spread like wildfire in the greenhouse sector. Learning-by-doing took place, as growers found out they could make a lot of money from selling electricity to the grid. According to the expert from Jenbacher, a large tomato grower that was one of the first to have installed a CHP was heavily surprised by the revenues he had made by selling electricity. Also, growers learned a

[8] The names of these mechanisms are predominantly of own design, and this also holds for some of the concepts. However, all of the mechanisms certainly exist in nature, and have their parallels in this technology diffusion case.

lot about trading strategies: "*We have met with a rebuff a couple of times, because we sold much too much [electricity]. We didn't need the heat at that moment. ... That is a learning process.*"

Survival of the fittest: All growers were more or less forced to investment in CHP as well, because they needed to keep up with their competitors. Although we have not found evidence of it, it may be that a late adoption of a CHP unit, or a bad operational trading and operation strategy, has caused some growers to go bankrupt. In general, the fierce competition in the greenhouse sector has caused a lot of bankruptcies and takeovers.

Imitation: Flower growers imitated CHP adoption and use from other industries. Some successful frontrunners of the third greenhouse-CHP type were imitated, like Prominent: "*Whether many growers have come to us after that Prominent investment? Yes, a whole flow was set into motion then. They have dropped by, yes. They said: If they do that, than it must be good, and then we are going to look and calculate ourselves if money is to be made with this.*". In the end, this resulted in a general inheritance of the technology within the greenhouse sector.

(Self-)Balancing nature of populations and ecosystems: The balancing of the supply and demand of CHP units and of electricity can be argued to resemble the balancing of e.g. hunters and preys in ecosystems. The increasing supply of electricity from CHP units, stimulated by increasing electricity prices, eventually reduced electricity prices, which in turn slowed down CHP demand[9]. Furthermore, the high demand for CHP units did lead to insufficient supply capability of CHP suppliers and delays in connection to energy networks by distribution system operators. The rising demand for CHP units also made these units more expensive: "*If things start going well because such a CHP is earned back within 3-4 years, then suddenly everyone wants such a thing, whereas there are not enough of them, so the price goes up.*"

Feeding of newly borns: One can argue that the feeding of newly borns by their parents in nature has a parallel with the provision of subsidies for CHP units. When the Dutch government found out that the CHP unit 'could stand on its own legs', it cancelled the feed-in tariff for electricity from CHP units.

Limited living space: As stated by van der Velden and Smit (2011), CHP technology 'competes with renewable energy, putting a brake on the growth of the renewable energy share'. In other words, the large adoption rate of CHP units in the Dutch greenhouse sector has significantly reduced the potential for renewable energy production by greenhouse companies. The greenhouse sector needs only so much electricity and heat, and the CHP units provide most of it. This might be compared to a fertile soil, which can sustain a limited amount of trees and plants.

Mutualism/symbiosis: Greenhouse companies with illuminated cultivation, i.e. flower and pot plant growers (first greenhouse CHP type) did not need a lot of heat, which is why they formulated CHP investment plans with a heat sale arrangement with a neighbouring greenhouse company (without a large CHP facility of their own). The flower grower would then benefit from additional income (or even turn CHP investment in a beneficial business case), while the neighbour would reduce its energy costs. One of the interviewed growers: "*What should I do with that [unused heat from the CHP unit]? Destroy it? That is a waste. So I want to deliver heat to a neighbour, and then you have to make sure that he benefits as well.*". However, such a mutually beneficial arrangement also causes some dependencies:

[9] This only happened at the end of the transition period, however, at which point most of the greenhouse companies with warm cultivation had already installed a CHP unit.

"*Imagine I make an investment and my neighbour becomes bankrupt, then I have a big problem"*. The latter quote appears an industrial example of 'obligate mutualism' (as opposed to facultative mutualism), a relationship in nature in which species are so dependent upon the mutually beneficial interaction that they cannot survive without it (Boucher, 1985).

6. Conclusion

The first and case-specific part of the research question, i.e. how can the diffusion of CHP units in the Dutch greenhouse sector in the 2000s be explained, has been answered by means of the identification of the key drivers. Five key drivers have been found for this particular technology diffusion process: the opening of the energy market in 2002, the high spark spread during the transition period, the compatibility of output of a CHP unit with greenhouse demand, the flexibility provided by the heat buffer, and the cooperative and competitive greenhouse sector culture. Parallel and interacting developments of technology, economics, policy, culture and ecology have contributed to the CHP diffusion, which is in line with the applied concept of the co-evolution of societal domains. Moreover, the CHP diffusion has not been specifically aimed at by the Dutch government, but rather evolved in a sector affected among others by (general and specific) policy measures. All in all, evolutionary mechanisms, similar to ones found in nature, have played a role in this case, as indicated by examples above. This points out the relevance of the theory of Universal Darwinism.

The second general part of the research question, i.e. what can be learned about the nature of technology diffusion from the case study, relates to the characteristics of technology diffusion. As technology diffusion always takes place in a socio-technical system, the co-evolving development of societal domains can be expected to create unique drivers for technological change, differing across domains, time, actors, and sectors. Thus, the evolutionary mechanisms and processes are a generic trait of technology diffusion, but key drivers are case-specific, and much more easily identified on hindsight than anticipated on in innovation policy formulation. Still, however, the consideration of evolution in sectorial developments may help in designing more efficient and effective policies for the stimulation of technology diffusion and innovation in the sectors considered.

In the case of the greenhouse sector, no strong incentives created by policy intervention were needed to realize CHP diffusion, but the opening up of the energy market was an important prerequisite, while earlier national CHP policy had already successfully embedded this technology into Dutch industries. Given the existing variety in social-technical systems, each technology diffusion case will necessitate a different degree, nature and content of government involvement in order for the diffusion to become a success. The analysis of evolutionary mechanisms has the potential to help identify key drivers for technology diffusion, and through that support policy making for innovation.

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Interviews

Stakeholder experts
AgroEnergy
Energy Matters
GE Jenbacher NL
LTO Noord Glaskracht
WUR Glastuinbouw

Greenhouse growers
A large tomato grower
A small tomato grower
An eggplant grower
An orchid grower
A rose grower