

Modelling Innovation Diffusion: A comparative system dynamics study between California, US and Denmark

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Abstract – Diffusion of renewable technologies are in the policy makers minds since 1970s to deal with depleting sources and finding solutions to environmental concerns. Therefore, understanding the mechanism behind a diffusion process becomes quite important for policy makers to understand and manage the process effectively. A new understanding of innovation diffusion is introduced by some authors in the recent years, suggesting a more focus on the dynamic understanding of the phenomenon. With this aim, this research used system dynamics modelling as a dynamic tool for modelling wind turbine diffusion. To be able to see to what extent system dynamics is able to capture the underlying mechanisms of diffusion process, a known case of wind turbine diffusion in California and Denmark are chosen as a comparative case study. The results showed that Denmark was more successful with higher and persistent diffusion rate due to various reasons; high oil prices, strong networks enabling knowledge share, and determination of the government. This research also showed that system dynamics is a promising approach for understanding innovation diffusion.

Keywords: Wind turbine diffusion, California, US, Denmark, Innovation Diffusion, System Dynamics

1. Introduction

Understanding the diffusion of innovation has a crucial importance for researchers and policy makers. Once the details of the causes and their interactions are clearly identified, managing the direction and the rate of diffusion becomes easier. Managing diffusion has gained more importance with the resource constrained and environmentally suffering world, since the need for clean energy and sustainable technologies become a must rather than a luxurious option. Both development of the new technologies, and adoption of those in society creates a challenge for the policy-makers. On such a critical issue, varied number of researches has been conducted.

Recently the researchers started to state that analysing innovation of diffusion needs new methods with a dynamic structure, because the technological change itself is dynamic in nature (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007; Jacobsson & Johnson, 2000). Therefore, static analyses of innovation diffusion remains inadequate explaining the reasons causing the behaviour of diffusion. This is caused by not being able to capture the indirect effects and time dependent effects of policies into the process. Instead, only the direct effects are captured in a black-box manner, without the knowledge of which policy affects which mechanism.

Mechanisms are defined as the building blocks of the system in this study. The definition given by Yücel is used for mechanism in innovation diffusion context, which is “*different manifestations of the change processes and interactions of the general scheme*” (2010). The mechanism is an interaction of different variables leading to a state change. These mechanism interact with each other on the basis of variables as well. To illustrate the concept, learning-by-doing mechanism can be used as an example. The cost of a new technology decreases over time with the learning coming from the experience gained in producing the same product over and over. This learning process can be seen as a mechanism with a starting point which is the initial cost of the product, an process of change due to the interaction of variables over time, which is the effect of

experience on better producing techniques and consequently on the cost, and a final state where a final cost that could possibly be a result of a mature technology with considerable experience. Learning-by-doing is a mechanism in this sense, and it can also interact with other mechanisms, such as the factors influencing the experience gained during production. In the end, addition of these mechanisms create a system description.

The idea of mechanisms in innovation diffusion theory is another representation of the need in dynamic approach. This research aims to reach an explanation for the reasons of innovation diffusion by defining an innovation system in terms of mechanisms. To do that, system dynamics modelling is used, where it is possible to represent and track the mechanisms in a transparent way. Also, a known diffusion story is needed to be able to see to what extent this mechanism approach with system dynamics is able to capture the diffusion process. For this reason, a well-known case of wind-turbine diffusion in California US and in Denmark are chosen for a comparative case study. Reading the same story with different glasses could bring a new perspective to the story, thus this case is analysed with system dynamics methodology with the dynamic mechanism perspective in diffusion literature. The next section introduces the dynamic understanding of the innovation diffusion in the literature with a short comparative literature survey. Then the third section gives information about the diffusion stories in California, US and in Denmark. The fourth section puts the information into system dynamics model. The results of this model is shown in section five and the last section concludes on the achievements and the limitations of the study.

2. Innovation Diffusion in the Literature

Diffusion of innovation theory starts with Rogers in 1983, and it has built on that a vast amount of studies since. Yet, since the theory has both social and technological parts and it occurs in a complex system which is the society itself, explaining why diffusion occurs or fails still is not exactly possible. On the other hand, tracing the activities impacting diffusion could be an invaluable information to policy makers. With that knowledge, they would not only be able to understand the diffusion in a deeper manner, but also how to manage those. With this aim, researchers brought explanation to key issues affecting the process of diffusion from different perspectives. Kemp, Schot and Hoogma explained the barriers to diffusion in 1998, Hekkert et al describe how the innovations *function* in the society to diffuse in 2007, and Yücel covers the mechanisms of transition in 2010. All of these concepts have similarities and differences, which are shown in Table 1.

Table 1 Comparative analysis of selected studies in innovation diffusion

Functions of Innovations (Hekkert et al, 2007)	Mechanisms of Transition (Yucel, 2010)	Barriers to Diffusion (Kemp, Schot and Hoogma, 1998)
F1: Entrepreneurial activities	Experience driven change in option properties	Technological, production and demand factors
F2: Knowledge development	Experience driven change in option properties	Technological, production and demand factors
F3: Knowledge diffusion through networks	Individual and social learning (Familiarity)	Cultural and psychological factors
F4: Guidance of the research	Commitment formation	Government policy and regulatory framework
F5: Market formation	<i>Not a mechanism but an activity affecting the purchasing decision</i>	Government policy and regulatory framework, Demand factors
F6: Resources mobilization	Resource driven change in option properties	Government policy and regulatory framework

F7: Creation of legitimacy	Preference structure change	Government policy and regulatory framework
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Table 1 shows the correspondence between the theories across Functions of Innovations, Mechanisms of Transition and Barriers to Diffusion. Function 1 says that entrepreneurial activities are the key drivers of experience for developing the technology, because the new entrants are more willing to take risks and innovative activities compared to existing manufacturers. Yucel also says that experience driven change in option properties help diffusion by accumulation of actor's experiences leading to improvement in product properties. Similarly, Kemp, Schot and Hoogma states that technological barriers due to low performance of new technology is not developed unless a certain level of production triggers the learning by doing mechanism, leading to an improvement in the technology and consequently increased demand.

Function 2 refers to learning by searching mechanism and learning by doing mechanism coming from not only the entrepreneurs but from all actors such as big firms and from the research centres. Yucel's experience driven change in option properties covers all learning by doing mechanisms and resource driven change in option properties implies the R&D spending and other resource allocation such as building research centres for a certain technology, and/or industry-government agreements. The negative functioning of these mechanisms can create a range of barriers according to Kemp, Schot and Hoogma, such as ill developed technology, and low scale of production and consequently low demand.

Function 3 is more about the demand side of the diffusion, mentioning the word of mouth coming from adopters and non-adopters. Similarly, individual and social learning of Yucel's mechanisms address the same concepts. These could be treated as a barrier when there is a negative word-of-mouth about the technology, if it does not fit with the expectations and the social norms of the adopters, which is categorized under cultural and psychological factors.

Function 4, the guidance of the research represents the determination of the authorities, adopters or the investors to focus on a certain technology among various alternatives. When the guidance is determined and the mind-set is created accordingly, instead of spending a lot of money towards different immature options, all the resources are allocated to the certain technology resulting in considerable improvement. Yucel addresses this issue by explaining the effect of commitment formation to the certain technology. For sustainable technologies, Kemp, Schot and Hoogma mentions that this choice of direction could be a barrier for other technologies for diffusion.

Function 5 covers the demand pull type of policies of government such as creating niche markets with pilot programmes or offering subsidies. This could be understood as an input fostering the demand for the new technology by affecting certain mechanisms. For example, if a subsidy is offered this would trigger more purchases and it will trigger the individual and social learning mechanisms. From the barrier perspective, it can be seen as a government intervention to the demand barriers.

Function 6 behaves as an input to Function 2, where the resources are allocated to contribute knowledge development by the government. Therefore the correspondence to Yucel's mechanisms are the same as Function 2, but since the government is involved, the corresponding barrier is mentioned as governmental policy in Kemp Schot and Hoogma's work.

Finally, function 7 stands for the demand for the new technology coming from the bottom, such as advocacy groups working for the legitimacy of the new technology. Yucel mentions this phenomenon by explaining the preference structure change for the actors where all the conventional options are not satisfactory and they look for the new options. However, existing regulatory framework may hinder

the development of the new technology, therefore this could be defined as a governmental barrier from Kemp Schot and Hoogma's perspective.

In this study, the categorization of these concepts are used as a base theory. For the cases of wind turbine diffusion in California and Denmark, whether the concepts mentioned in Table 1 exists or not is analysed, and then their interactions are conceptualized.

3. Wind turbines in California and Denmark

The diffusion story of California starts with the oil crisis of 1973. With the oil crises of 1970s, U.S. government started to seek for alternative solutions for energy, to reach a more secure energy supply. Electricity generation from the wind turbines were one of the possibilities in this regard, because it was the only promising technology among renewables in terms of cost-competitiveness at that time (Menz & Vachon, 2006). Also, a secondary reason was important to policy-makers, due to urban fog and acid rains during 1970s, the environmental concerns had begun (Norberg-Bohm, 2000). With these concerns, there were several policy attempts to stimulate wind turbine installations in the U.S. As a result of these policies, about 95% of wind turbines in US are installed in California, due to additional state policies to the federal ones and favourable weather conditions (Sawin, 2001). It is possible to categorize these policies in supply-push and demand-pull policies, where supply-push policies aim to stimulate innovations, whereas demand-pull policies try to create market for new technologies.

Supply push technologies are easily visible from R&D spending. Until 1977, R&D budget was rather low for all energy types, but Department of Energy decided to increase the budget about six times (Norberg-Bohm, 2000). Yet, with the change of the government policy with Reagan's administration, the budgets were cut drastically and it remained low until 1999 (Norberg-Bohm, 2000). In total, from 1975 to 1988, US spent \$427.4 million on R&D only for wind technology (in real dollars).

Demand push policies in US started with the Public Utilities Regulatory Policy Act (PURPA), which was published in 1978 and implemented in 1981. This policy required utilities to purchase power from "qualifying facilities" which are defined as small renewable heat and/or electricity generators (Martinot, Wiser, & Hamrin, 2005). PURPA is the ancestor of feed in tariff of today, however the cost calculation was different. The cost was determined as "avoided cost", which is the marginal cost for a public utility to produce one unit of power (IEPA, 2014). The calculation of this cost was left to the states, but the aim was to approximate the avoided costs of the utilities (Martinot, Wiser, & Hamrin, 2005). In 1980, California offered 25% state tax credit for investments in wind power, which was the same amount of federal tax credit. Federal tax credit had ended in 1985, and state tax credit was reduced in 1985 and ended in 1987 (Sawin, 2001). California took PURPA act to a further stage by offering long term contracts at a fixed electricity price for the first 10 years, in which the contract duration varies between 15 to 30 years (Martinot, Wiser, & Hamrin, 2005). This was a real stimulant in California wind market, but only for a short period of time. This offer started at the end of 1983 and continued until 1985. In 1991, there was a new tax credit for wind power. The federal government offered 1.5 ¢/kWh reduction on electricity cost for wind with Energy Policy Act. The implementation of these policies and corresponding wind turbine installations can be seen in Figure 1.

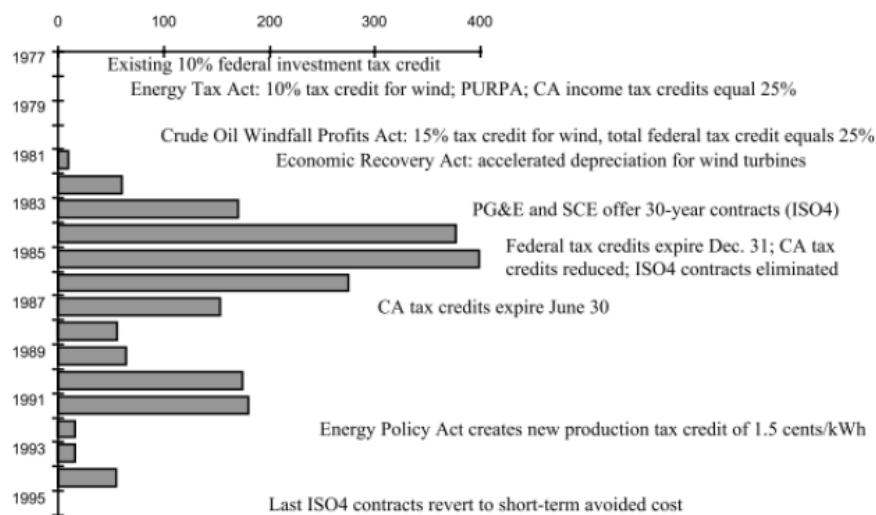


Figure 1 Annual Wind turbine installations and the policies in California (Norberg-Bohm, 2000)

In Denmark, the wind turbine energy topic is raised during the same time, where the main motive was oil crises of 1970s. Denmark had no energy source of its own, therefore they were highly dependent on imports. In 1973, 94% of Denmark's energy supply was coming from imported oil and the rest was mainly based on coal, which was also imported (Kamp, 2002). Environmental concerns were also on the rise, and it took a significant role on determining Danish energy policy for the following years. Society was strongly against nuclear energy, therefore Denmark had no other choice than wind turbines, since other renewables were far away from being cost competitive. Similar to United States, Danish wind turbine policies followed two paths: supply-push and demand-pull. Under the supply-push policies Risø National Laboratory and Technical University of Denmark started Wind Power Programme, to develop knowledge about large wind turbines (Van Est, 1999). In the first phase of this programme, 35 million DKK was spent on developing wind turbines, and the 82% of this budget went to development of large wind turbines.

Apart from putting R&D efforts into wind energy, the Wind Power Programme directly involved the utilities in the programme, since they will be the potential buyers of the technology. This involvement helped utilities to be more familiar with the technology from the development phase, which could be also interpreted as a demand-pull policy (Kamp, 2002). The development of small scale wind turbines in Denmark started independently from R&D spending, with the efforts of small entrepreneurs. These entrepreneurs were in favour of small, locally owned power plants instead of centralised power plants. Besides, the society was environmentally conscious, therefore their mind-set was highly in favour of renewables instead of nuclear energy (Sawin, 2001). Therefore the Danish government provided clear aims to the producers by stating that they want to reach 10% wind share in electricity generation by 2000 (Olume & Kamp, 2004). they want to reach 10% wind share in electricity generation by 2000 (Olume & Kamp, 2004). In 1979, the Danish Ministry of environment ordered utilities to provide wind turbine access to the grid and pay the fair rates for the electricity they generated. They provided 30 percent of the investment cost payment. This reduction was given to buyers of wind turbines, not to the producers (Buen, 2006). It should be kept in mind that, this subsidy was given to the wind turbines which are approved by Risø Test Station assuring quality. Also a Danish wind atlas was published showing the best locations for siting wind turbines in 1980-1981. In 1985, there was an agreement with the government and utilities for 10 years. Utilities were able to buy the wind generated electricity by paying 85 percent of its price. This

policy resulted in increase in wind turbine installations. In 1986-87 investment subsidy was reduced to 20% and 10% respectively. And this subsidy was removed totally in 1989 (Kamp, 2002). Also the criteria for receiving the investment subsidy were tightened. In 1988, there was a new agreement between the government and the power companies to install 100 mW wind power at the end of 1990. However, this agreement was only totally realized at the end of 1992 (Buen, 2006). Figure 2 shows the overview of policies over time and the wind turbine installations per year in Denmark during 1976-2002. The figure can be interpreted as the visual representation of the policy procedures and their effects on wind turbine installations.

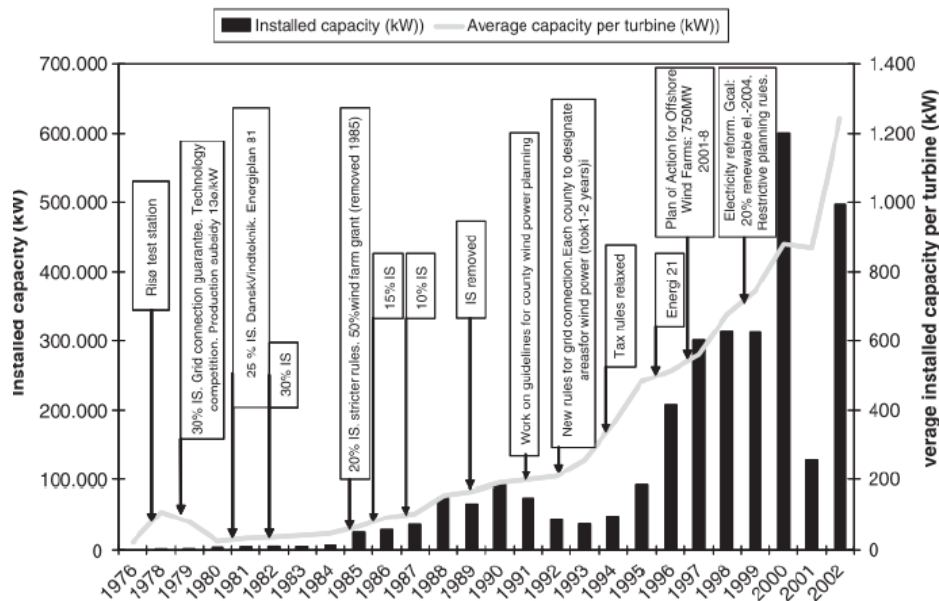


Figure 2 Annual Wind turbine installations and the policies in Denmark (Buen, 2006)

Apart from the policies in these cases, it is important to look at the market structure and the relevant actors for understanding the diffusion processes. In both cases, the electricity market was deregulated at that time, and there were three main actors in the field. Regarding wind turbine technology, the wind turbine producers were one of the main actors and they aimed to maximize their profits by increasing the market of wind turbines. The more reliable and well performing wind turbines they produce, the more demand is created. Another main actor consists of the utilities. It is assumed that the electricity production was under the responsibilities of utilities, even though in real life they purchase some of their electricity need from independent producers. The reason for this assumption is coming from the aim of utilities which is minimizing the cost of electricity. With this aim, the utilities look at the marginal cost of electricity produced internally or externally, and they make their purchasing decisions accordingly. Therefore, even though they purchase the electricity from independent producers, or they produce it themselves, the investment cost, fuel cost, operation and maintenance cost and all other costs are reflected on the electricity cost that the utility produces/purchases. This cost is called levelized cost of energy (LCOE). LCOE is the cost of electricity to reach the break-even point over the lifetime of the project for generating it from a specific source (NREL, 2013). The number of independent producers were considerably more in Denmark than California, because the deregulation process had just begun in the United States. However, Danish government apply sanctions on the utilities to share the production costs of these independent producers of wind energy. For these reasons the actors producing electricity are considered under the utilities. The third important actor was the government, and no distinction is made between the state and

the federal government, since both of them imposed policies regarding wind turbine diffusion. In both cases, the aim of the government was to foster the diffusion of wind turbines without threatening the equal opportunities of the market players.

The main similarities of these cases in terms of mechanism introduced in Table 1 are; there was no other alternative which could make commitment formation necessary (F4) since wind turbine was the only alternative in terms of cost competitiveness. Also, creating of legitimacy (F7) was not necessary, since the government itself wanted to have cleaner energy. Entrepreneurial activities (F1) were existent in both cases resulting in reduction in investment cost and improvement in capacity factor of wind turbines with learning-by-doing mechanism. Knowledge development function (F2) was also active in both cases, which is triggered by R&D investments of the governments. Knowledge diffusion through networks (F3) is also active in both cases, because this function implies the individual and the social learning of the new technology via direct experience of the adopter, or hearing, seeing or talking about the new technology. For the wind turbine installers, the individual learning mechanism was active, whereas of the other utilities which are considered as potential adopters, social learning mechanism was active. Market formation (F5) was provided in a similar manner in both cases with the suggestion of subsidies, instead of creating a niche market or making a pilot programme. Finally, since there were no competitive environment among the new technologies, and the wind turbine was the only alternative to the conventional technologies, resource mobilization (F6) is not affected from other technologies, only key-point was the governmental mind-set and the budget.

These similarities show that both cases have the same diffusion structure with the same active and inactive mechanisms. Yet, the way these mechanisms work created the difference between the two cases. For instance, the knowledge diffusion through network was stronger in Denmark compared to California, because the government involved the utilities into the development of wind turbines from the beginning, Danish Windmill Owners Association published a monthly magazine and brought wind turbine owners and potential adopters together with conferences from the early phases of the wind turbine development (Kamp, 2002). Another difference between California and Denmark was coming from the determination of the Danish government and the society on adopting wind turbines as an energy source from the beginning. They saw the wind turbines as an only alternative, because they could not have any resources for fuel for conventional technologies, and they did not want nuclear energy with the security and environmental concerns. Last but not the least, even though the oil crises affected both countries, Denmark was affected more of this, because the average cost of producing energy from conventional sources was nearly three times more than the United States, which made an expensive option as wind turbines more affordable.

4. Model Description

For modelling wind turbine diffusion with system dynamics, the active mechanisms mentioned in the previous section are used. Since both cases have the same active mechanisms, the structure of the model is the same for both cases. In Figure 3, the overview of the mechanisms and their interactions is shown.

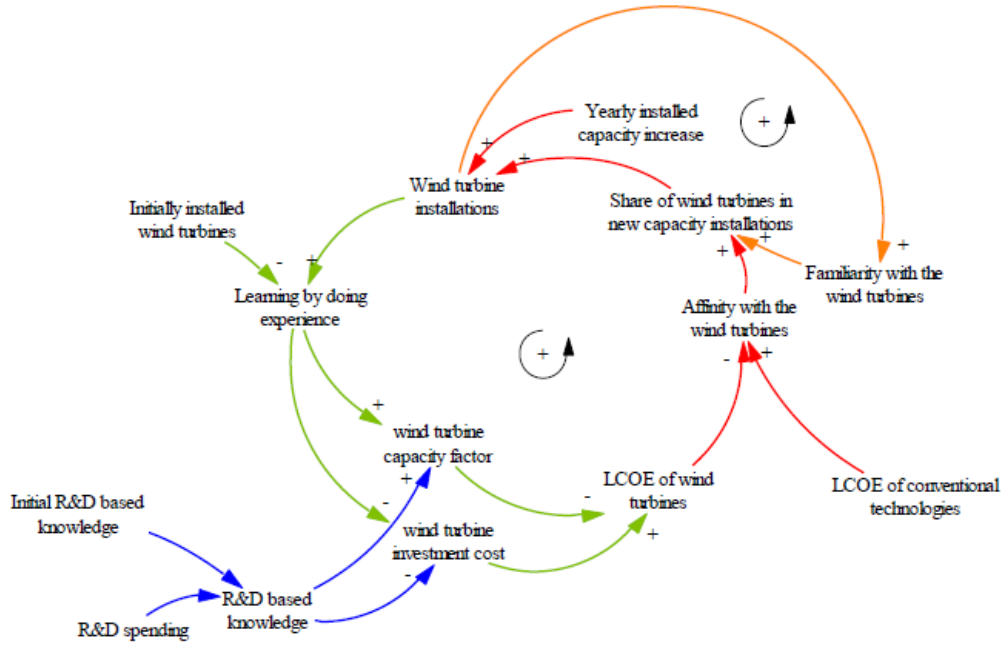


Figure 3 Model structure - active mechanisms and their interactions

The function 1 and 2, which contains learning by searching and learning by doing mechanisms are modelled with the two factor learning curve formula (Kouvaritakis, Soria, & Isoard, 2000). The formula for cost improvement is as follows:

$$SPC = A. \left(\frac{CC}{CC_0}\right)^{-\alpha}. \left(\frac{KS}{KS_0}\right)^{-\beta} \quad (1)$$

In this formula (1), SPC stands for the investment cost per unit for the technology (specific cost) and CC is the cumulative installed capacity at a given time, which is divided by the cumulative capacity at time 0 (CC_0). $-\alpha$ is the learning factor, and A is the specific cost at time 0. KS stands for the knowledge stock at a given time, measured by the R&D investments of that year. KS_0 is the initial knowledge stock and β represents the learning by searching factor, which is the representation of percentage improvement on the investment cost coming from learning by searching process, similar to $-\alpha$ representing the percentage improvement of learning-by-doing process. This formula is also adopted for performance improvement of capacity factor, with positive α and β values.

Affinity with the wind turbines represents the probability of an actor to purchase wind turbines by comparing it with the conventional technologies. Modelling affinity and familiarity is adopted from Struben & Sterman's work on electric vehicle adoption (2008). The formula of affinity is based on standard multinomial logit choice models, which is a commonly used framework in modelling consumer choice among the different options in the consideration set. In this case, the consideration set consists of wind turbine vs. conventional technologies:

$$a_j = a^* \exp\left(-\delta \left[\frac{LCOE_j}{LCOE^*} - 1\right]\right) \quad (2)$$

Formula (2) represents the affinity of wind turbines based on LCOE. a_j is the affinity towards wind turbines at a given time, where a^* represents the reference affinity for the reference LCOE value

LCOE*. The reference value stands for a normal value that the adopter has an idea about. For example, an actor decides whether the given LCOE of the available options are expensive or not by comparing it with the reference LCOE*. If the given LCOE is more expensive than the reference value, the affinity decreases and vice versa. The reference values are determined separately for conventional technologies and for wind turbines. For conventional technologies, the average LCOE of all times is taken as LCOE* and then affinity at this value is assigned as 1, because, on average price of electricity generation cost, the utilities will go for the conventional methods. After determining reference values of conventional technologies, wind turbine reference values are determined accordingly. Assuming that if wind turbine is competitive with the conventional technologies, the affinity to the wind turbines is assigned to 1 with lower reference LCOE* value, since it is a relatively new technology and utilities will have questions in their mind for going for a new technology. Besides there will be switching costs of the utilities for moving to a new technology, due to limited experience and unknowingness of the new technology. This way affinity is modelled as a decision making process of utilities for purchasing wind turbines. Detailed formulation of LCOE is given in (3):

$$LCOE_t = \frac{EAC}{E_t} + M_t + F_t \quad (3)$$

where

$$EAC = \frac{I_0 \cdot r \cdot (1 + r)^n}{(1 + r)^n + 1} \quad (4)$$

EAC stands for equivalent annual cost representing the cost per year of owning and operating an asset over its lifetime (Short, Packey, & Holt, 1995). I_0 represents the overnight cost of the project meaning if the project was completed overnight (no interest rate was taken into account). E_t stands for the electricity generation in the year t , r stands for discount rate, n represents the lifetime of the project (which is 20 years for wind turbines), M_t represents the operation and maintenance cost in the year t and F_t represents the fuel cost in the year t . Utilities made their decision based on this LCOE in the model with the corresponding affinity to the LCOE of that year.

However, to be able to consider wind turbines as an option of energy generation, the actor should be familiar with it. Knowledge diffusion through networks is another important parameter for the diffusion process, therefore familiarity should also be modelled. Modelling familiarity is also adopted from Struben & Sterman's study (2008). Familiarity is a stock variable changing between 0 and 1, where 0 represents no familiarity with the technology and 1 represents that all adopters and potential adopters are familiar with the new technology. Familiarity gain is determined by the social exposure coming from marketing campaigns, individual learning and social exposure coming from the users, and finally the social learning standing for the social exposure coming from non-users, which is word-of-mouth. The formula is shown below:

$$n_t = a + c_i F \left(\frac{W}{N} \right) + c_j F \left(1 - \frac{W}{N} \right) \quad (5)$$

In the familiarity gain formula which is illustrated in (5), a represents the social exposure gained by marketing/awareness programmes c_i represents the effectiveness ratio of the users, F represents the familiarity value at time, W represents the installed mW of wind turbines, N represents the total installed capacity for electricity generation in mW and finally c_j represents the effectiveness ratio of non-users on adoption.

Familiarity also decays over time, when there is not enough social exposure. This decay occurs in a non-linear way, because if the level of social exposure is low, familiarity decays very fast, but if the level of social exposure is high. This is modelled with the following exponential function (Struben & Sterman, 2008):

$$\phi_t = \phi_0 \frac{\exp(-4\epsilon(n_t - n^*))}{1 + \exp(-4\epsilon(n_t - n^*))} \quad (6)$$

This function which is a characteristic logistic function, n_t represents the social exposure from users, nonusers and awareness campaigns at time t . n^* represents the reference rate of social exposure where familiarity decreases at half of the normal rate. The greater the exposure, the slower is the decay. ϕ_0 is the maximum familiarity decay rate. Familiarity decreases fastest when n_t is small. ϵ stands for the slope of the decay rate at a given point. It is assumed that ϵ is $1/n^*$ which normalizes the elasticity of the familiarity decay to exposure at 1.

With all of these formulations, the main mechanisms of the wind turbine diffusion and the model structure is set. Then, as a next step, the initial values of exogenous variables are set, and the corresponding policies are implemented into the models. The initial values of variables which are different in both cases are shown in the appendix.

Before going through the model results, a brief explanation about the validation work should be given. Boundary adequacy tests, Structure confirmation test, parameter confirmation test, dimensional consistency test are applied for seeing the validity of the model's structure and the model tests these tests. Then structure oriented tests called extreme condition test and behaviour sensitivity test is conducted, and the results showed that the model behaves as expected under extreme conditions, and it is numerically sensitive to most of the variable value changes about 10%. This numerical sensitivity indicates that the model is robust and it is able to capture the main dynamics of diffusion stories in California and Denmark.

5. Model Results

The initial results of the model for yearly installations of wind turbines is shown in Figure 4, with their fit to the real wind turbine installations. Also, the behaviour of the models without any policy interventions are shown, indicating the results of different initial conditions of these cases (Figure 5).

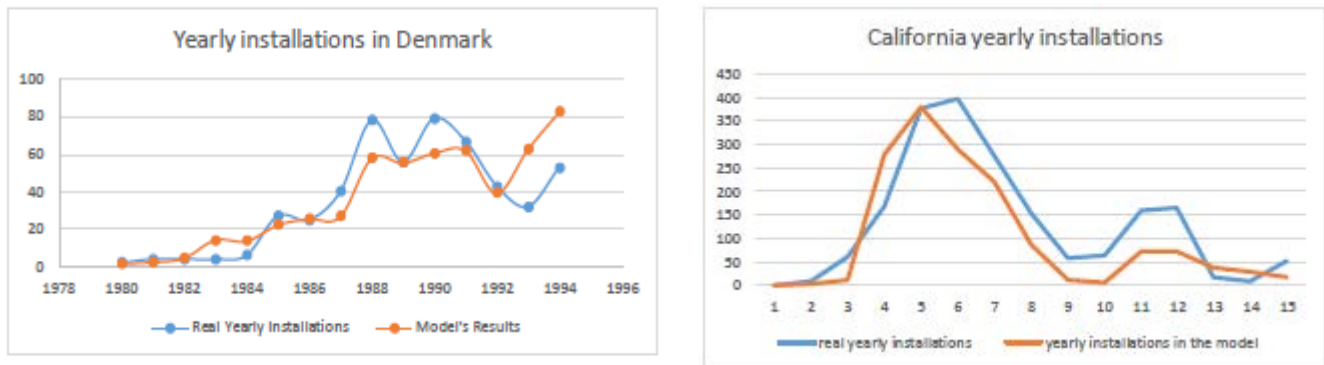
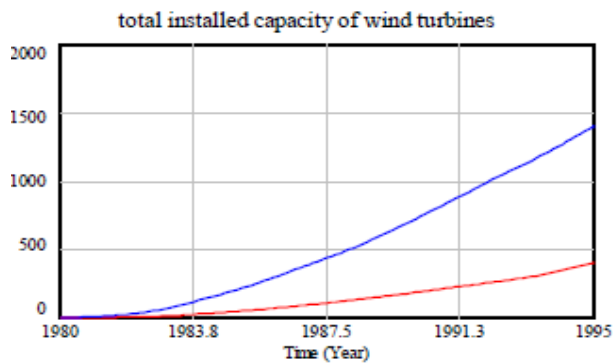


Figure 4 Comparison of model's results and yearly wind turbine installations in real cases

Denmark



California

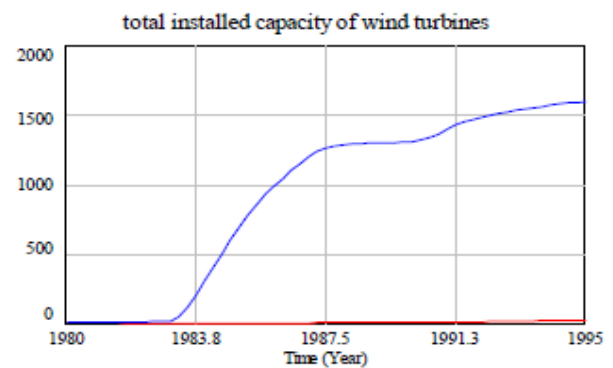


Figure 5 Cumulative Wind turbine installations with and without policies

As the base results of the model in Figure 4 shows, the model is able to capture the stories of innovation diffusion. This shows that, using system dynamics for modelling innovation diffusion can be added to the range of analysing methods.

As it is clear from Figure 7.1 the initial settings lead to a considerable amount of installations in Denmark whereas there is such little installations in California. The reasons for this can be explained with these combined effects of variables:

- First of all, utilities in Denmark are more sensitive to price changes in energy, because they purchase all of the resources from outside at very high prices compared to California. This situation results in easy switching to a new energy alternative, since their satisfaction with the current ones are not that strong.

- Secondly, the effectiveness of users and non-users for triggering adoption is higher in Denmark, and this is beyond the power of government, because this effectiveness was coming from the bottom, where the investors and entrepreneurs worked together for effective communication in Denmark. Such a movement is not observed in California case. When the effectiveness of users and non-users are stronger, this triggers the feedback mechanism of familiarity, and familiarity has a multiplicative effect on demand share of wind turbines. In a way, it is a percentage value representing the rate of utilities who are aware of the advantages and disadvantages of wind turbines. Without awareness it is not possible to consider the wind turbines as an option. This ratio was higher in Denmark as a result of triggering more adoption.

- The learning curves were also effective in these results, but in a subtle way. The key criteria for adoption is to have a profitable value for wind turbines compared to conventional technologies, not to have the lowest value in the global market. Since the cost of conventional technologies was already high in Denmark, with the cost reductions coming from learning curves, it was easier to reach the desirable LCOE in Denmark. On the other hand, in California, the cost of generating electricity from conventional sources was already cheaper, and as a result, the learning curves had to be more effective to reach a desirable cost. For this reason, Denmark was more promising for wind turbine diffusion initially, which already creates an advantage for the diffusion process. However, without any policy intervention, the rate of innovation diffusion would still be low in Denmark, which is not promising to reach the stable adoption of the S-curve. Thus, it would be wrong to conclude that the policies were not the real reasons for fostering wind turbine diffusion. For this reason, policy tests are conducted to

see the effects of policies in fostering wind turbine diffusion. All policies are implemented in isolation to observe the sole effects on increasing the diffusion, and also all-but-one type of policy tests are conducted by removing a policy from the full model to see whether there is a policy that hinders the installation rate. Additionally, the policies existing in one of the cases but not in the other one are also added to the other model to see what would be the possible consequences of that policy. For example PURPA act type of policy did not exist in Denmark, but for a what-if analysis it is put to the Danish model. The results per each policy is explained below briefly:

- Effect of R&D investments on wind turbine installations triggers the learning-by-searching mechanism, leading to a decrease in LCOE of wind turbines and making it a more attractive option for the utilities. However, the results showed that this effect is quite small for fostering wind turbine installations. It is important to note that, in total United States spent 538.5 million (in 1980 \$) from 1980, where in total it spent 200 million from 1970 to 1980 for R&D of wind turbines. On the other hand, Denmark spent 33.9 million from 1980 to 1995, and they spent 12.5 million from 1970 to 1980 which was treated as an initial value (Sawin, 2001; Norberg-Bohm, 2000). These results show that, learning by searching mechanisms are not enough for effective diffusion, because it takes time to reach a cost competitive results for a new technology only by learning by searching. In the meantime, since the new technology is expensive, there is no or little adoption, and this situation results in a decrease in familiarity, because familiarity requires a certain ratio of social exposure. One of the main sources of social exposure is the adopters, and the word of mouth coming among non-adopters about the technology, which is not triggered effectively in this policy.

- Effect of subsidies on wind turbine installations aims at the demand for wind turbines by directly influencing the LCOE of it. the subsidies in general are more effective than R&D efforts, but they do not contribute to the diffusion significantly. The Energy Policy Act remains ineffective when it is implemented in isolation, because since the learning by doing mechanism is inactive due to low installations, the cost reduction is not enough to make wind turbines competitive with 15 \$ subsidy per MWh. It is also important to note that the effect of investment subsidies are also as good as the subsidies offered on LCOE, because a significant part of LCOE belongs to investment cost in wind turbine technology, since there is no fuel cost and little operation cost.

- Effect of PURPA act on wind turbine installations shows that this policy is quite effective in California, making the cost effectiveness of the wind turbines closer to the conventional technologies. However, this policy did not show great effects on Danish case, because the affinity to wind turbines remain lower in Denmark model, because the utilities expectations for wind turbine costs with full affinity has a greater gap between the average value of the LCOE of conventional technologies.

- EnergiAct policy represents the determination of Danish government in setting wind turbines as the only energy alternative and determining persistent goals for wind turbine share in energy generation. This policy has a soft effect similar to marketing, making the option visible to consumers. However, such a mechanism is not observable in California, due to rapidly changing policies and governmental mind-set towards renewables. Therefore, to see the possible effects of EnergiPlan act on California's installations, this policy is added to the California model. The results show that in isolation EnergiPlan act also does not have a significant effect, because even though the familiarity plays a significant role in adoption, it is not sufficient by itself, because if the option remains expensive, people would not purchase it. Therefore, the effect of this policy is also tested with the other ones and the results showed that awareness campaigns in addition to demand-pull policies have significant effects in fostering diffusion.

- As an extension of PURPA act, California offered long-term contracts for installing wind turbines. There were no such an offer in Denmark, therefore this policy is implemented to the Denmark model

to see the possible effects. This policy creates a temporary demand for installing wind turbines, but the effects are not as strong as the PURPA act. The results of the Danish case also shows similar results.

-Denmark decided to install wind turbines of 100 mW with the government funding with an agreement with the utilities from 1988 to 1992. There were no such an attempt in California, therefore to show the possible results this addition is modelled to see the possible effects. Shows that the effect of governmental installation has a temporary bump in the installations. Also, the familiarity changes are checked for this external installation and the model shows almost no change in familiarity. The reason for this is because this installations are coming externally, it is an additional mW to yearly need of demand, and it does not affect the yearly installations done by utilities or cooperatives. Therefore, the share of wind turbine installations do not change, and in total the percentage of wind turbines on installed capacity changes insignificantly, since 100 mW has less than 0.1% effect on the share. This value affects the social exposure from users and non-users but since the impact itself is quite small, there is no long-lasting effects of government installations of wind turbines.

The model showed that the differences between California and Denmark cases are coming from twofold. First the initial settings in Denmark shows that it provides a more suitable environment for wind turbine diffusion with stronger network, expensive LCOE of conventional alternatives, high sensitivity of adopters to price due to fluctuating and expensive market, and positive mind-set towards wind turbines. On the other hand, in California, the conventional alternatives were already cheaper which requires wind turbines to be improved much more to be cost competitive. Also, people have no interest in building networks regarding wind turbines, which also resulted in decreasing familiarity with the wind turbines and consequently less installations. Apart from that, the market was more stable in conventional technologies, which made the utilities to be reluctant in switching into a new technology. All of these initial conditions resulted in a less promising environment for wind turbine diffusion in California compared to Denmark.

Although the initial setting were in favour of Denmark, the policy interventions exist to counteract these negativities. From policy making perspective, we see that the most effective policies in both cases are in demand-pull policies by offering subsidies and feed in tariffs. Denmark case showed that it is also important to create awareness about the new technology to increase its adoption rate. The models' results also showed that the direct interventions on installing wind turbines such as long term contracts in California and government installing wind turbines in Denmark has temporary effects on diffusion whereas the effects of stimulating markets also impacts the adoption in the future due to increased familiarity and triggered learning by doing mechanism. R&D efforts also improve the adoption, but it has effects to a certain extent, therefore spending vast amounts on R&D is not a desirable policy according to the results of the model.

6. Discussion and Conclusion

This research can only be seen as an early and humble attempt to explain the innovation diffusion with a more dynamic approach, compared to widely used methods such as regression analysis. This study showed promising results in modelling innovation diffusion, by looking at the diffusion stories occurred in the past. This way it was possible to observe the abilities of system dynamics method in capturing the different diffusion paths. This could be an indication for future studies, with the suggestion of forecasting the direction of a certain technology in the society with planned policies. In a way, from a reflective study to an explorative study is possible with system dynamics.

Another issue realized in this research is about the diffusion of innovation literature itself. Different attempts to give the diffusion studies a more dynamic approach has been tried, but these attempts remained theoretical so far. This study was also an attempt to apply these theoretical suggestions into

case studies. To test the validity of these theories, more case studies should be conducted with the other well-known diffusion stories. This way, the strength of these theories will be supported.

In the literature of technology based innovation systems, similar issues are mentioned by different researchers, but a common framework showing the relationships of these theories do not exist to the author's knowledge. A common framework showing these similarities and the common issues raised by different researchers could be a useful guide for the following diffusion studies. The Table 1 can be interpreted as a preliminary attempt for creating such a framework.

It should be noted that the conditions and the mind-sets of the actors has changed in wind turbine diffusion since 1980s. At that time, the knowledge about environmental hazards coming from the conventional technologies were only at the initial stage. Therefore, there was no green demand coming from the consumers, and the utilities only focused on the profit side of generating electricity. Yet, this is not the case in today, the amount of environmentally friendly consumers increased, demanding green energy from the utilities even at a higher price. The change of this mind-set offers a new research area, for understanding the change in people's mind-set and the factors affecting this change. Apart from that, the actor's mind-sets should be reflected into the diffusion studies for more realistic results.

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Appendix

Variable	CA	DK	Comments
Alpha value for learning by doing on capacity factor	1.07	1.07	Capacity factor learning did not show significant changes between CA and DK, therefore in the model, this variable is treated as a global value with the same values.
Alpha value for learning by doing on investment cost	0.88	0.947	When we look at the investment cost at 1980 and investment cost at 1995, we see that CA had much impressive learning curve compared to DK. To capture this effect in the model, alpha and beta values of CA is given higher than DK. Also, as Hekkert et. al mentions, learning by doing is hugely affected from entrepreneurial activities (2007). In Denmark the entrepreneurs were producing agricultural equipment before, therefore they learned slowly with trial and error (Karnoe & Garud, 2001)
Beta value for learning by searching on capacity factor	1.04	1.04	Since capacity factor is treated as a global value, this learning effect is also the same. The reason it is lower than alpha value is based on literature (Kamp, 2002).
Beta value for learning by searching	0.9	0.96	The reason to have lower value for CA which results in better cost reduction is due to available data. Note that these beta values are also less effective compared

on cost			to alpha values which is based on literature (Kamp, 2002)
Effectiveness of contacts of nonusers	0.3825	0.45	Since the communication among potential adopters in DK was higher than CA due to published Naturlig Energi magazine where the performances of wind turbines made public (Kamp, 2004). For this reason, the effectiveness of contacts of non-users are assumed to be 15% less in CA.
Effectiveness of contacts of users	0.68	0.8	Communication between the users of wind turbines were also higher in DK due to Wind Meetings where knowledge and experience were shared between manufacturers, owners and researchers. They also established Danish Windmill Owners Association (Kamp, 2004). For this reason, the effectiveness of contacts of users are assumed to be 15% less in CA.
Initial familiarity	0.25	0.25	Initial familiarity with the wind turbines were low but not zero for both cases. Both CA and DK had historical experiences with wind turbines (see Chapter 3 and 4) and they were familiar with the windmills. There were no real indication of familiarity difference between two cases in the literature, therefore they are assumed to be the same.
Initial installed capacity for electricity generation	55000	7072	This number is based on EIA data, reflecting the real values.
Initial investment cost of wind turbines per kW	2500	1322	This data is taken from the literature and converted to 1980's dollar value. (Sawin, 2001; Lantz et al 2012).
Interest rate	0.6588 (mean) 0.0265 (stdev)	0.7757 (mean) 0.0172 (stdev)	The interest rates are also taken from the literature (Sawin, 2001).
Maximum decay rate	0.425	0.425	Maximum decay rate for both cases are assumed to be same, because this value represents the reference value for forgetting rate. Due to differences in cultures this number could differ, but in general, people tend to forget the new technology when the exposure is not frequent enough (Struben & Sterman, 2008). Since this situation is valid both for CA and DK the same value is used in the simulation.
Normal social exposure	0.2	0.2	Similar to maximum decay rate, this value represents the reference value for forgetting rate. When it is 0.2 it means that familiarity decays with the half of the maximum decay rate. Since maximum decay rate is assumed to be the same for both cases, it is reasonable to take the same reference value for normal social exposure, ensuring the decay behaves the same for both cases.
Operation cost of wind turbines	14.19 (mean) 3.53 (stdev)	12.73 (mean) 3.391 (stdev)	These costs change over time, therefore their mean and standard deviation is given in the table.
Percentage increase of installed electricity capacity per year	2.5%	2.5%	This values are also calculated on average, by looking at the net changes of installed capacity between 1980 and 1995 (EIA, 2012). The average capacity increase per year for both cases turned out to be the same
Sensitivity value for wind turbines	1	1.8	The reason for taking Danish utilities' sensitivity values higher than California is due to market's results. When weighed average cost of conventional methods and LCOE of wind is examined, it is observed that standard deviation of the prices is much higher in Denmark compared to California. This situation implies an insecure market structure with more sensitive buyers to price. The numbers are calibrated with the fit to historical data. For both values DK values are 1.8 times higher than CA.
Sensitivity value for conventional technologies	0.54	1	
Weighted average cost of conventional methods (Average LCOE)	24.87 (mean) 2.607 (stdev)	61.61 (mean) 11.63 (stdev)	These values are based on historical data. Since the value changes over time the mean and the standard deviation is given in the table. As it can be seen, the prices are more stable in California.

LCOE of wind	31.75 6.95	56.83 19,68	These values are calculated by the model, but to show the changes in the price over time it is added to the table.
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