Assessing transition trajectories towards a sustainable energy system: A case study on the Dutch transition to climate-neutral transport fuel chains

KEY WORDS

transition management; backcasting; sustainable fuel chains; technological trajectories; technological change; radical change; incremental innovation; case study

SUMMARY

This paper proposes a method for the ex ante *evaluation of technological trajectories. As a case we study the Dutch transport energy system and its transition to climate neutrality. Two technological trajectories are proposed: (i) a sequence of transition steps based on* radical *infrastructural change, and (ii) a sequence of steps oriented towards* incremental *innovation on the side of the vehicle. The system is approached from a multi-actor perspective, taking into account the multiplicity of views and interests of actors involved. Based on interviews a quick scan is made in terms of their Willingness to Participate (WTP). We find that on long term goals, a positive WTP and a high degree of consent are the case. For the short term the opposite is found. Management should therefore be directed at facilitating short term innovations: in the case of an incremental strategy, by stimulating market development; and in case of a radical strategy, by providing finance and institutional legitimation.*

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INTRODUCTION

Since the release of the fourth issue of the Dutch National Environmental Policy Plan (NMP4) in 2001, attention has been drawn to the management of a transition to a sustainable energy system. The major issues associated with the sustainability debate are security of supply, air pollution, and climate change (Goldemberg, 2000). A possible solution for these problems could be the utilization of cleaner and renewable energy sources. However, stimulating the energy system to transform in the direction of sustainability is not an easy process. The reason for this is that apart from technological components, energy systems consist of various interacting organizations, interlinked by physical and social infrastructures. The dynamic interactions between continuingly changing groups of companies and institutes (or *actors*), impose a large degree of complexity and uncertainty onto the system. Furthermore, as a result of huge past investments associated with the infrastructural networks, the system is by nature rigid. So, bounded by inertia and veiled by complexity, the energy system is unlikely to transform according to our desires, without a lot of intelligently coordinated effort being put into it. For a broader account on the process of social change and collective action see Schon (1971). Coordinated effort may begin with the creation of insight in the desired directions of change. Then foresight and technical planning studies can create insight in the technological routes that could be taken. In our case we consider two different *transition trajectories* that may lead to a more sustainable energy system. The method of evaluation of these trajectories in terms of realization potential is the central theme of this paper.

The objective of this study is to develop an instrument that may be used to support decision-making processes regarding transition management. The energy system will be approached from a multi-actor perspective, thereby taking into account the multiplicity of views and interests associated with the actors involved. As a case study the Dutch transition to climate-neutral transport fuel chains is chosen. Our method is to provide information on the attitudes held by the relevant actors but it should also provide an insight in the factors that 'determine' their viewpoints on the various transition steps. In this way it can also be used as a heuristic instrument for policy makers who want to stimulate transition.

The article is structured as follows. The theoretical section gives an overview on our conception of transition. It describes the nature of transitions and complex systems and what conditions have to be met in order to initiate changes. Next, the method of research is described and the case to which it was applied. The results section is a condensed account of our findings and interpretations. Finally the problems and limitations of our way of analysis will be discussed and a conclusion with respect to its value will be given.

THEORETICAL FRAMEWORK

In this paper we follow past approaches to the analysis of technological change in which technical systems are decomposed in terms of functions, and in terms of the actors that occupy or operate these functions (Rosenkopf & Nerkar, 2001). We conceptualize transitions in two ways, first from a systems perspective and second from an agency perspective.

Systems perspective

From this outlook, a transition is defined as a major technological transformation in the way that societal functions such as housing, transportation, or energy supply are organized (Geels, 2002). In the current tradition two different research directions can be distinguished. The first is to study and learn from technological transitions from a historical point of view. For instance the study of the historical transition in the Dutch energy system, where coal as the dominant fuel is replaced by natural gas in the 19th and first half of the 20th century (Rotmans et al., 2000; Verbong, 2000). In the second research direction these historical examples are used to conceptualize technological transitions in order to answer questions on the origin of transition and the nature of particular patterns and mechanisms in transition processes (Geels, 2002). An important result of this approach was the development of a heuristic multi-level model based on Rip and Kemp (1996) and Kemp et al. (2001) that describes transitions trajectories in terms of changes that start at the micro level (or niches) and for which success is largely based on developments at the meso level (called regimes) and at the macro level (called landscapes).

Contrary to these research directions, we are especially interested in creating insight in transitions that are at the verge of taking place (future transitions). The insights from studies named above are very relevant from a 'sociology of technology' and historical point of view but they do not lead to concrete insights with respect to the way transition processes can be practically influenced today. Besides, the concepts derived from these studies may have a totally different meaning in a varying contexts. We therefore choose to study future transition trajectories in a specific technological domain. We assume that transition trajectories have a specific direction, which can be influenced. In accordance with this idea, we adopt the backcasting approach as developed in the Dutch Sustainable Technology Development (STD) program (Weaver, 2000). This approach starts with a strategic problem orientation of the current transition direction, which is followed by the definition of a desired future image of a technological system or sector. Examples are the biomass based chemical industry as an alternative to the current oil based chemical industry and sustainable building practices as an alternative to current building practices (Weaver, 2000). Thus, for the specific domain that we study we determine the desired final stage of a transition trajectory. The next step is to intelligently define a number of radical and systemic innovations, or transition steps, which collectively form the transition trajectory. Ideally, these steps are more or less functionally discrete in the sense that they represent partial changes in the energy system, which can be technically realized without necessarily changing the functional activities in other parts of the system. In our case, this division in steps is more or less natural since these functional activities correspond with a specific type of technology and infrastructure. As a consequence, it becomes possible to associate specific groups of actors with these activities. The separate transition steps can be regarded as small transitions on their own and since the number of activities and actors involved in these transition steps are a lot smaller than for the transition as a whole, the problem becomes easier to grasp. Different orderings of simultaneous and chronological innovations lead to different transition trajectories. See Figure 1 for a schematic overview of different orderings of transition steps resulting in different transition trajectories which all lead to the same final system configuration.

Agency perspective

Transition steps only take place due to a collective action of a group of actors. The dynamics of systems in transition are constituted by the behavior of the organizations that make up the active dimension of the system. For this reason this study takes off from the level of individual actors. The actor perspective is analyzed in two ways. First of all actors judge technical options and their stake in it individually. Yet, this is in a sense rather unrealistic, because actors are group members, who will try to behave consistently, and reliable. For this reasons actors relate their own judgment to that of so-called 'significant others' in the field. Due to the fact that for each system component a number of

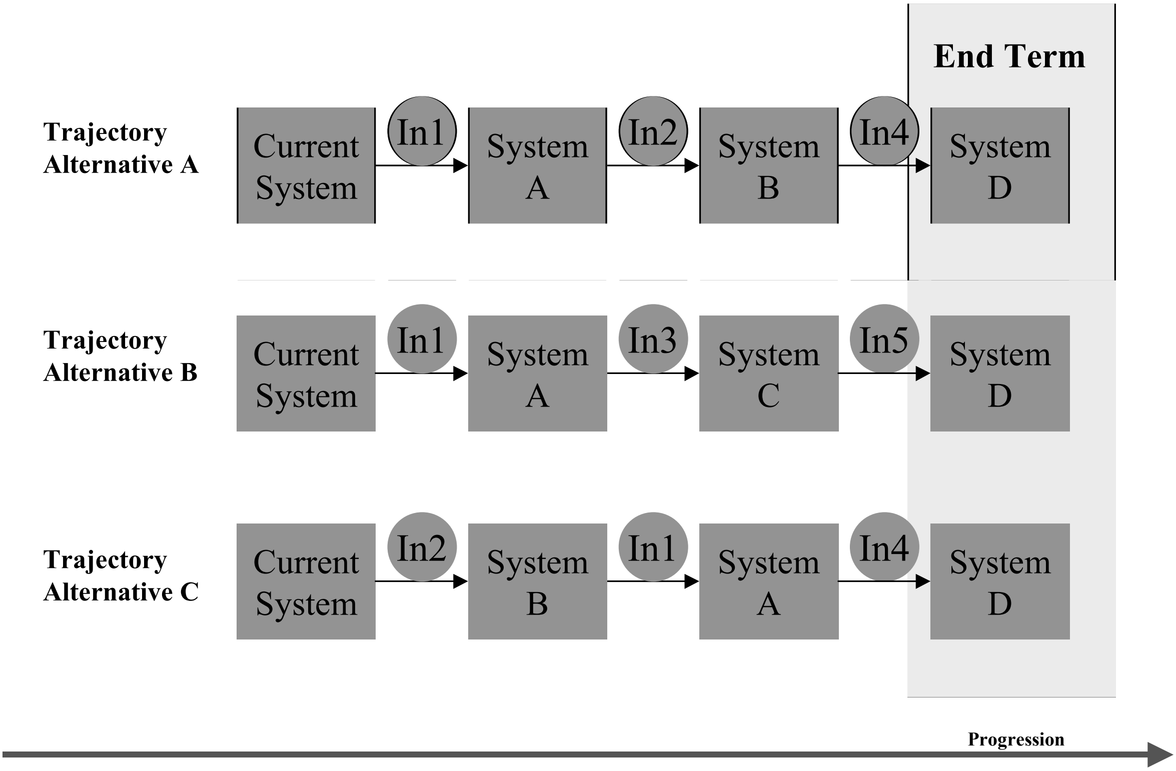


FIGURE 1: Three possible transition trajectories: differences in type and sequence of system innovations (In 1–5) lead to different system progressions; in this way with a limited number of possible innovations, a large number of trajectories can be designed, all leading to one 'ideal' system configuration, the transition's end term.

relevant stakeholders is available, system transitions imply network dynamics in each step of a transition trajectory. For a more elaborate analysis of these so called band wagon effects see Fiol & O'Connor (2003).

In our study a transition is considered as a sequence of steps, where the steps are defined ex ante, as taken for granted (which they are not of course). Actors basically have three options *in each step*: (i) they can decide to jump on the bandwagon, (ii) they can wait with jumping on the bandwagon, and (iii) they can decide that they do not have any stakes and abstain from participation all together. Our theoretical model builds on the idea that decisions as to participate in trajectories are 'rationalizations' of planned behavior and the expected benefits and costs. *Across steps* actors have the choice between presence and absence, where specific combinations have their own ramifications, depending on their relative influence. Fundamental to the whole idea of transition management is that the initially loosely coupled actors will become a group with a team spirit that helps to find productive compromises and can live with constructive conflicts. The formation of a sense of direction, the extent into which actors will be able to form an efficacious group with power (i.e. a coherent chain of transition steps) is one of the key factors in organizing momentum for technological change.

The individually perceived desirability and feasibility of a transition step result in an individual judgment and accompanying attitude with regard to what will be called the actor's Willingness To Participate (WTP). It is assumed that for realizing a transition step at least two conditions must be met. In the first place a dominant positive attitude towards changes and future effects related to the respective transition step, and secondly a majority of the relevant actors that shares this attitude. This convergence will result in a critical mass that initializes and lobbies for the project needed to implement transitions. A situation with a moderately positive attitude shared by all actors ('optimistic') is considered to be more stimulating for a successful transition, than a situation with a higher average willingness but a low degree of consent. So besides a clear 'go!' situation two other modes remain, namely a situation with consent and an average negative willingness ('pessimistic') and a situation without consent ('uncertain'). Figure 2 shows a scheme of these three extreme transition step types. The boxplot gives median values and data dispersion (the broadness of the quartiles). Dispersion is considered as an indicator for dissent (the inverse of consent). Our basic proposition is that a higher convergence is positively correlated with a positive willingness to participate. So the actors' average WTP, together with the level of consent, serves as indicator for determining a transition step's realization potential.

In order to be able to evaluate transition trajectories this analysis should be done for multiple transition steps. The sequence of steps serves then as an important frame of analysis in the evaluation. It is the 'pessimistic' and 'uncertain' transition steps that create the bottlenecks of a transition trajectory. So our basic proposition here is that the larger the number of steps in a transition trajectory with low feasibility, the larger the likelihood of either failure or delay. From a managerial point of view it is insufficient to identify transition failure or delay. One needs an explanatory framework that accounts for differentiated levels of WTP. If we want to have a (limited) possibility to influence a transition it is necessary to find out what factors influence an individual actor's WTP. For this, we basically build on the theory of reasoned action in which behavioral intentions are considered a function of the valuation of a behavioral (technological) option and the likelihood that the option is

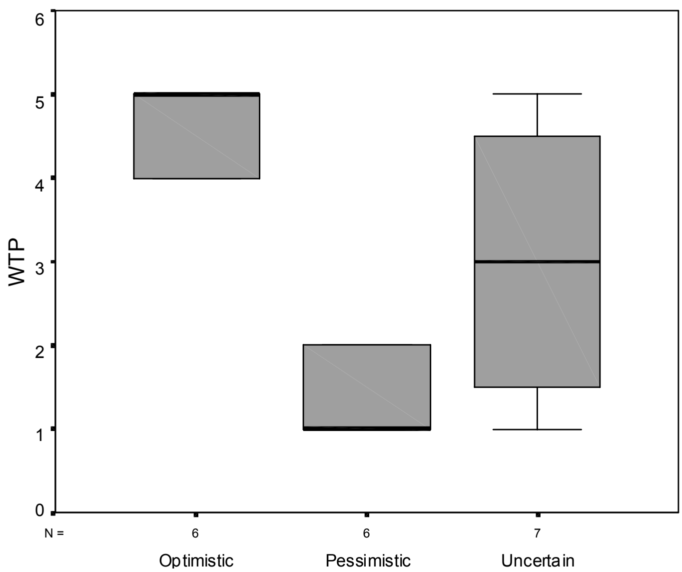


FIGURE 2: Three typical transition step types

feasible. In our model the valuation of an option is the aggregate of actors' judgment on a large set of social, economic and technological criteria.

In order to find the most important among these supposed determinants of actor behavior a model was constructed consisting of 24 criteria. This was done with the aid of a literature survey and during a workshop with academic experts. The criteria are grouped in three main clusters: desirability, financial barriers and feasibility. Each criterion is clearly defined and a hypothesis was given on the expected relation with actors' WTP (either positive or negative). Figure 3 gives a schematic outline of the model. A short description of the criteria is given in Appendix 1.

METHOD

With regard to the methodology of our study, three aspects are of importance. Firstly, in order to arrange the possibility to test the proposed evaluation instrument a case was defined. This case had to involve a relevant (existing) problem that is sufficiently complex in terms of actor diversity and the necessity of infrastructural rearrangements. After a short literature survey, the case of climate neutrality within the transport fuel energy system was considered to be suitable. Secondly, interviews

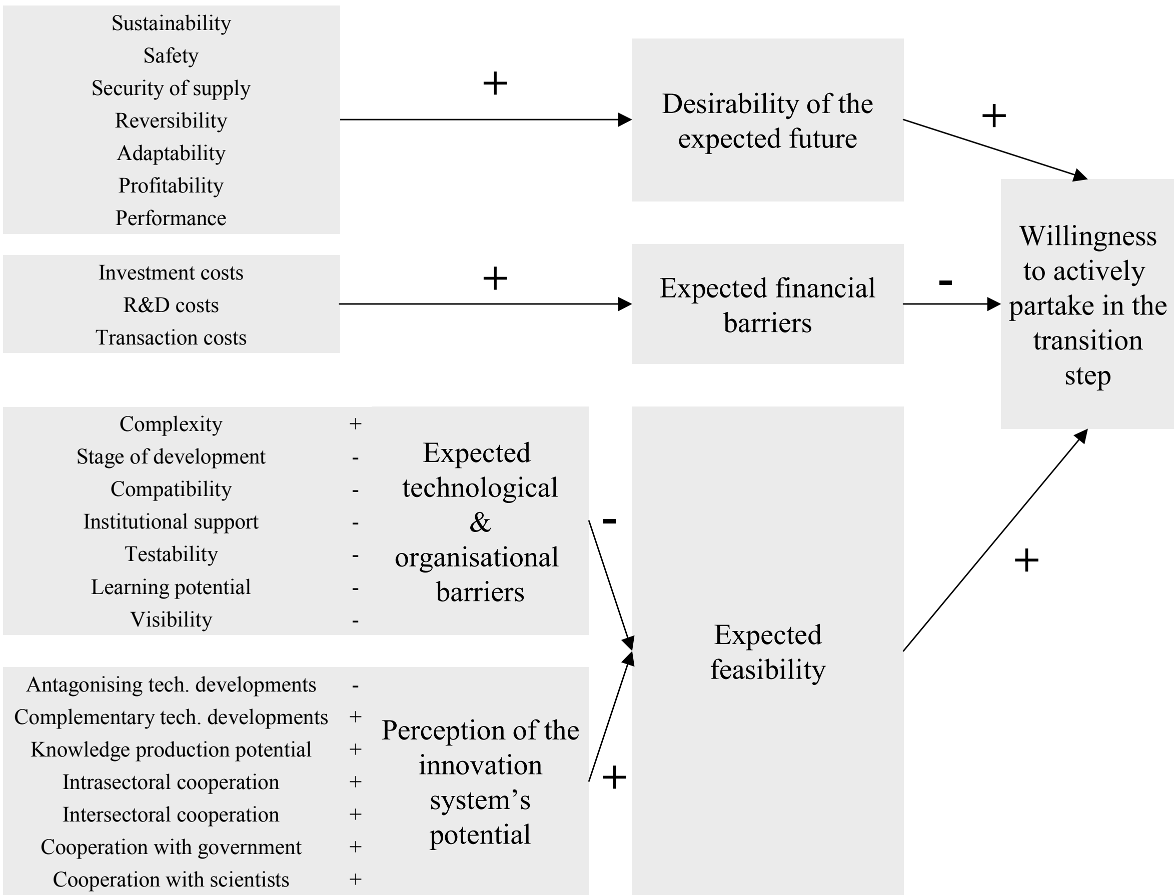


FIGURE 3: Possible determinants of an individual actor's WTP

were arranged with representatives from a wide variety of companies and institutes. The objective of the interviews was to gain insight on the general attitude of actors within the context of the case and to determine WTP and criteria scores. The third step was to interpret and statistically analyze the data. In the remainder of this section, the case characteristics are given, and subsequently the interview contents and the method of analysis itself will be presented.

The case of climate-neutral transport fuel chains

The climate problem with respect to the transport fuel sector is relevant since in the Netherlands, about 15% of all GHG-emissions can be ascribed to the combustion of transport fuels (NOVEM-ADL, 1999). Moreover, the combustion of fossil fuels results in emission of NOx and SO2, which results in local air pollution and acidification problems. By developing new technologies it could become possible to reduce these emissions or prevent them altogether. However, the problem is complex because of the high degree of interdependence between different actors and the rigidity of the infrastructural framework which keeps it together. A large number of potential innovations are emerging but most of them require lots of research and infrastructural adjustments. These adjustments are usually highly specialized with respect to a particular technology; therefore choices have to be made in advance. Before elaborating more on the innovations mentioned, it is useful to give an outline of the main components of the transport fuel energy system and its structure.

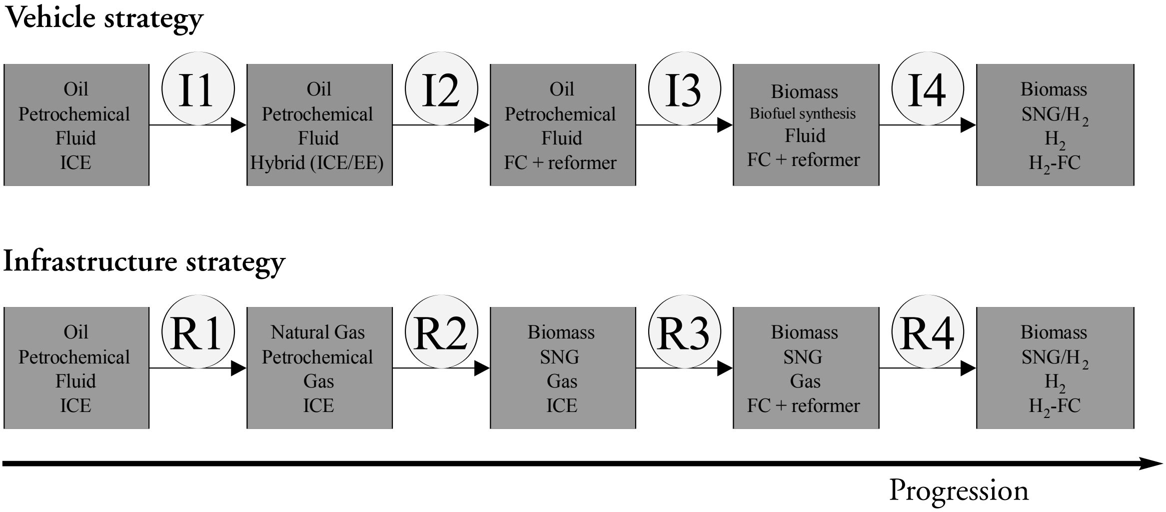
Transport fuel chains

The transport fuel energy system can be considered as a chain of interdependent activities, performed by a variety of actors. Ideally, these actors cooperate as far as they are intersectorally related to each other (i.e. when they engage in activities which are functionally dependent on each other) but actors will also compete with each other, mainly when they are intrasectorally related to each other (i.e. when they engage in functionally equivalent activities). The transport fuel chain makes up the core of the transport energy system. A typical transport fuel chain consists of the following system components:

- Exploration and production of primary energy carriers
- Transport and distribution of primary energy carriers
- Chemical conversion to secondary energy carrier (transport fuel)
- Transport and distribution of fuel to filling stations
- End-use

In the current situation, practically all fuels are derived from crude oil, which is extracted by a relatively small number of large oil companies in notably the OPEC countries. After transport by pipeline, ship or other means, the oil is chemically converted (i.e. refined) to liquid substances like petrol, diesel or LPG. These liquids are distributed to filling stations by pipes and tanker trucks. Filling stations provide the consumers with fuel for their cars. The majority of cars is powered by an internal combustion engine (ICE). Apart from the mentioned technological system components, the system also consists of companies and institutes with a facilitating role. Examples of these facilitating activities are maintenance, education, government regulation, research, technology development etc. It should be made clear that the energy system entails much more than the fuel chain alone. The system's components are usually constituted by a variety of actors but they can also be made up by a single company or institute. Of course a single actor can also be active in more than one system component.

Based on literature and expert judgment,



Boxes represent fuel chains, with system characteristics given as indicated:
1. Primary energy source; 2. Conversion technology; 3. Type of tank-infrastructure; 4. End-user technology

FIGURE 4: Two transition trajectories representing two possible policy strategies

three alternative transition trajectories leading to a hydrogen powered transport fuel chain are composed, based on two potential transition strategies: an infrastructure directed strategy and a vehicle directed strategy. In Figure 4 an overview is given for each of these different trajectories. An elaboration on the two strategies is given below.

Vehicle directed policy

Denoted by 'I' for incremental. In this case, the first step is to gradually equip all cars with hybrid engines. Fossil fuels will be used for long distance transport but for 'city traffic' the cleaner electric engine will be used. The electric engine is powered by a battery, which is charged when the ICE is in practice (I1). The next step is to gradually replace the ICE's by fuel cells with on-board reformers, which have a better performance than ICE's. Conventional fuels can still be used (I2). Now a gradual shift to liquid biofuels becomes possible. Many promising technologies are being developed, so a variety of options is available. Most biofuels allow mixing with fossil fuels, so a gradual change is possible (I3). If desirable (because of energy efficiency reasons for example), a final transition step to a complete hydrogen infrastructure is possible (I4).

Infrastructure directed policy

Denoted by 'R' for radical. An immediate change in the existing physical infrastructure could clear the way for future developments. Within this trajectory, large investments are made in order to build a natural gas distribution system. Gaseous fuels may replace fluid fuels on a relatively short term (R1). After the change of infrastructure, a shift to biogas (SNG) becomes possible. Depending on the development stage of biomass production and conversion technology, a gradual mixing of gaseous biofuels will be possible (R2). Now a climate-neutral system has been reached, the next possible step is to equip cars with fuel cells (FC) and reformers, in order to increase energy efficiency and decrease non-CO2 emissions (R3). Eventually a shift to a complete hydrogen infrastructure is possible, when the existing gas distribution network is gradually adjusted and extended to carry hydrogen (R4).

Within the framework of this study multiple companies and institutions were contacted. They are grouped according to the sector they are part of. Since some of the representatives do not want to be named, they will be referred to with the following codes.

- Gas companies (G1, G2)
- Oil companies and energy companies (OE1, OE2)
- Car manufacturers (C1, C2, C3)
- Government institutions (M1, M2, M3)
- Science and knowledge institutes (S1)

The interviews

In order to get the information needed, interviews were arranged with a number of actors, covering the system as much as possible. The goal of these meetings was to (i) ask the actors' opinion on the desirability and feasibility of the proposed transition steps and trajectories, (ii) determine their functional position with respect to each transition step and (iii) determine quantitative scores for their willingness to participate and for each criterion with respect to the separate transition steps. The interview survey consisted of a number of open questions and a questionnaire directed at obtaining criteria scores on a 5 point Likert scale. The open questions are meant to obtain a broad general insight in the actor's view on the transition problem and to determine his exact position within the context of the problem (i.e. to meet the first two goals described above). The questionnaire was developed to meet the last goal. The criteria as presented in Figure 3 were operationalized with respect to the transport fuel system. This is necessary because their significance is context dependent. In Appendix 1, an overview of this description is presented. Criteria scores are obtained by stating questions specified for each transition step.

The analysis

First of all the actor's WTP is determined. Secondly, from the combined views of multiple actors, the degree of collective WTP on the transition step level is estimated. And finally, an attempt is made to combine these separate transition steps in a sensible way to form desirable and feasible pathways for a complete system transition. The nature of the information obtained by this survey leaves the possibility of a qualitative as well as a quantitative approach to the problem.

The qualitative analysis entails the presentation and evaluation of all information of a narrative nature. Main points of interests are: (i) the actors' functional position within the system, considered now and in the future, (ii) the actors' visions on the system in relation to its transition and (iii) the actors' attitudes towards the transition in relation to the problems experienced. The quantitative analysis is aimed at the question which transition steps are the most probable. If it turns out possible to construct rationally feasible trajectories from probable ('go!') transition steps in the terms described above, this could point out potentially successful transition trajectories and exclude others. 'Go!' situations are identified by finding the transition steps where a general consent has been reached on WTP in a positive way. The degree of consent was determined by aid of a statistical dispersion function. In order to determine if and how differences in WTP are related to the criteria as proposed in the former section, a Kendall's tau-b correlation test was performed on the relation between each criterion and WTP for each transition step.

Results

First the two proposed transition trajectories will be subjected to an analysis with respect to WTP and the degree of consent. Results will be explained according to insights gained during the interviews. In the second part the results of the criteria analysis will be presented.

Willingness To Participate (WTP)

Table 1 gives the measured WTP scores for all interviewed actors and all transition steps. A graphical representation is given in Figure 5 where WTP scores are measured along the vertical axis. Along the horizontal axis the transition steps are indicated for the two trajectories in chronological order. The boxplot gives a median score (indicated by a bold line), the division of quartiles (four intervals each containing 25% of measured data) and the maximum and minimum value. In the theoretical framework we explained that the steps with higher WTP scores are more likely to be successful than the steps with a low WTP. The range of dispersion can be interpreted as the degree of dissent among actors with respect to that particular transition step.

Analyzing the steps

Figure 5 clearly shows that in the incremental trajectory the first two steps are most problematic. For the first step (I1EU) the median score is not very positive and the dispersion is quite large. In the second step the large degree of dissent is the main obstacle. The third step is not as problematic as the first two; it contains one low outlier but a relatively high median score. The last two steps are considered as the most unproblematic. Median WTP scores are 4 or higher with only a small degree of dissent. For the radical trajectory things look somewhat different. Most striking are the initial low WTP scores for the first two transition steps (introducing natural gas infrastructure and natural gas vehicles). In a way these are the most characteristic steps for the trajectory but scores are mostly below 2, which means that the actors are not willing to engage in these steps. The third step (R2BF) is equivalent to the third step (biofuels) within the incremental trajectory. WTP is relatively high with an exception for one actor. The R3EU step is equivalent to I2EU; a positive WTP combined with a high degree of dissent, which is problematic. The last two steps are essentially the same as the last two steps within the incremental trajectory. Due to the very problematic start of this trajectory, the radical trajectory appears to be less plausible than the incremental trajectory.

Table 1: The actor's WTP scores for all transition steps within two transition trajectories; averages and standard deviations are given for each transition step.

Actor	I1EU	I2EU	I3BF	I4EU	I4IS	R1EU	R1IS	R2BF	R3EU	R4EU	R4IS
G1					5		5				5
G2				4	5		2			4	5
OE1			1					1			
OE2		5		5	5				5	5	5
C1	3	1		5		1			1	5	
C2	3	5		4		3			5	4	
C3	2	2		5		2			2	5	
M1	5	4	5	3	4	1	1	5	4	3	4
M2			4		4		?	4			4
M3			5		2		2	5			2
S1			4		4		2	4			4
Average	3.3	3.4	3.8	4.3	4.1	1.8	2.4	3.8	3.4	4.3	4.1
SDV	1.3	1.8	1.6	0.8	1.1	1.0	1.5	1.6	1.8	0.8	1.1

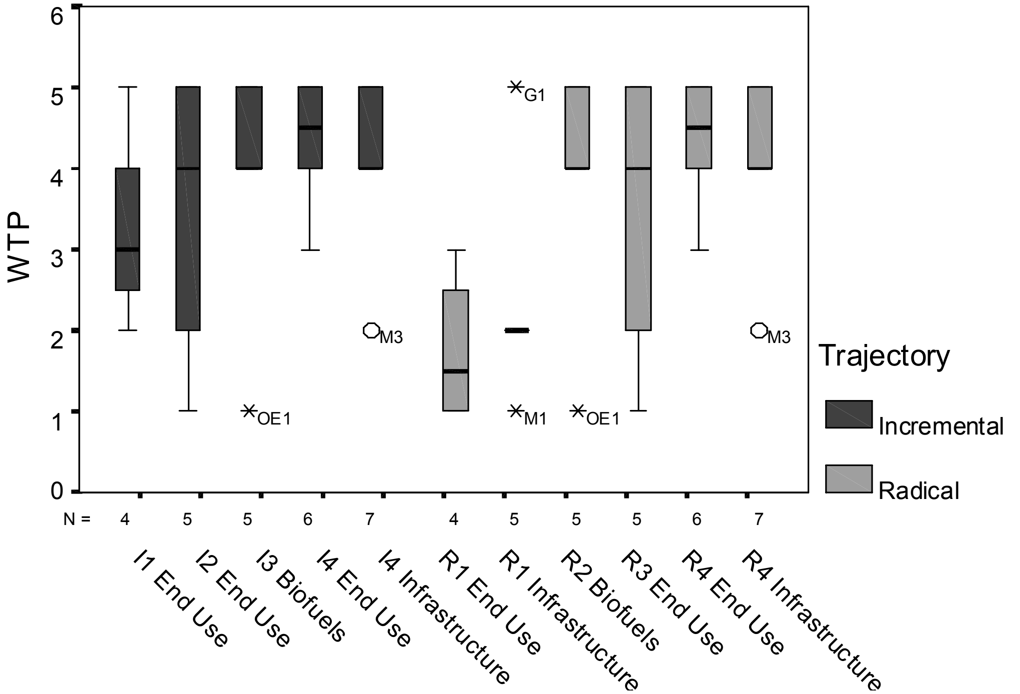


FIGURE 5: Boxplots of WTP scores for transition steps of two possible transition trajectories

Analyzing the trajectories

What is most visually striking in the WTP pattern is the upward curve that can be recognized in both trajectories. With respect to the more distant steps, WTP scores are more positive. This may be explained in several ways. The first is that It seems that the further in the future a transition step occurs, the more positive actors tend to be. The basic sentiment may be that in the future it will be much easier to organize such a dramatic change due to increased technological knowledge. An other cause might be the fact that the last transition steps are based on hydrogen as energy carrier, which was found to be a desirable end term to begin with. This would imply that when these two steps would be modeled earlier in time, a positive WTP would still be expected. From interviews it became clear that all actors have very high expectations of hydrogen as a fuel but they all realize that this is an option for the very long term. A positive implication here is that the end-term is generally perceived to be desirable and feasible. If the initial bottlenecks can be overcome the transition might continue in the generally desired direction in a relatively smooth way. The negative implication is that the initial situation is characterized by uncertainty and negativity. Perhaps the futuristic imageries of a hydrogen economy combined with the vague financial responsibilities on the short term, creates a form of security/certainty with respect to the long term future.

It is important to notice that the development of a hydrogen infrastructure and the use of hydrogen as a transport fuel is regarded by all actors as a transition step that they are willing to take, whereas the natural gas based transition steps (which clearly offer sustainability advantages as compared to conventional fuels; see Hekkert et al. (2004) for an energy analysis of different natural gas based fuel chains). are regarded as negative. Again the explanation can be found in the location of the steps in the sequence that makes up the trajectory or in the perceived benefits of the transition steps. Another interesting pattern is the clearly negative relation between median WTP scores and dispersion range. The higher the WTP, the stronger the consent is. This supports our hypothesis on this matter.

The final point that we want to discuss based on this pattern, is the necessity of intermediate transition steps to reach a final transition state. Lessons learned from historical transition trajectories show that add-on and hybridization technologies often occur. This means that technologies in an early phase physically link up with established technologies (Pistorius & Utterback, 1997; Geels, 2002). Our case shows that transition steps that intentionally have been incorporated as hybridization technologies or intermediaries do not score as well as expected (e.g. hybrid vehicle, natural gas vehicle, biomass fueled vehicle). A possible explanation might be that the costs associated with innovation in the energy/transport system are so high that hybrid technologies do not exist long enough for a good return on investments. Another explanation might be the European focus of this research. Japanese car manufacturers are known to have developed interests in hybrid technology much earlier than European car manufacturers (Hekkert et al., 2003).

Transition determinants: finding policy targets

In the previous section various transition steps have been labeled as problematic due to a large dispersion in WTP scores. The purpose of this section is to find out which criteria strongly determine the WTP scores for these difficult transition steps. Table 2 shows the Kendall's tau-b correlation coefficients for all criteria related to the actors' WTP in five transition steps that are regarded as problematic. The table shows that most criteria show significant correlations with WTP in one or more transition steps. This leads us to conclude that we have selected a number of important criteria that influence WTP. We tried regression analysis to reduce the number of relevant criteria for each transition step and to correct for multicolinearity. However, due to the small sample size no robust model could be extracted. For space and clarity reasons we will not discuss every criterion in detail but instead we focus on the general pattern across steps.

What we clearly see in Table 2 is that for different transition steps, the distribution of significant correlation coefficients among the criteria clusters strongly varies. We discuss the transition steps at the level of criteria clusters as indicated in Figure 3: desirability, financial barriers (costs), techno-organizational barriers, and innovation system potential.

For the first transition step (I1EU, hybrid vehicle technology), the largest share of criteria can be categorized under 'desirability' and 'expected financial barriers'. Also some techno-social criteria seem relevant. This seems logical since this transition step concerns the introduction of already developed technology and besides WTP is mostly determined by car manufacturers. Therefore arguments like price (costs), sustainability and stage of development are logical incentives.

The second step (I2EU, hydrogen reformer technology) does involve new technology and cooperation between multiple actors is necessary both in the development and implementation stage. This difference in the type of transition is visible in terms of the criteria that determine WTP. For here, the largest share of significant criteria is found among 'socio-technical barriers' and 'innovation system potential'. The fact that cooperation with science and government is important combined with a strong sensitivity for criteria like testability, learning potential and visibility, indicates the current typical niche character of this transition step.

The third step (R1EU, natural gas vehicle

TABLE 2: KENDALL'S TAU-B CORRELATION COEFFICIENTS FOR ACTORS' WTP AND CRITERIA; 1-TAILED SIGNIFICANCE LEVELS ARE GIVEN BETWEEN BRACKETS AND SAMPLE SIZE IS INDICATED BY N; BOLD UNDERLINED CASES ARE SIGNIFICANT AT P<0.1.

	Criterion	I1EU	I2EU*	R1EU	R1IS	I3BF+
Desirability	Sustainability	**0.78 (0.079) N=4**	**0.83 (0.030) N=5**	–0.40 (0.222) N=4	0.43 (0.175) N=5	**0.71 (0.068) N=5**
	Safety	0.00 (0.500) N=4	0.25 (0.284) N=5	0.40 (0.222) N=4	–0.43 (0.175) N=5	–
	Security of Supply	–	–	–0.82 (0.110) N=3	–	0.18 (0.355) N=5
	Reversibility	**0.80 (0.063) N=4**	–0.14 (0.384) N=5	**–0.78 (0.079) N=4**	0.00 (0.500) N=5	–
	Adaptability	0.00 (0.500) N=4	–0.12 (0.394) N=5	0.00 (0.500) N=4	–0.52 (0.173) N=4	–
	Profitability	**0.80 (0.063) N=4**	**0.82 (0.061) N=4**	**1.00 (0.000) N=2**	0.18 (0.359) N=4	0.12 (0.394) N=5
	Performance	–0.40 (0.222) N=4	0.25 (0.284) N=5	**0.89 (0.051) N=4**	–	–
Costs	Investment Costs	**0.80 (0.063) N=4**	–	0.00 (0.500) N=4	0.00 (0.500) N=3	–0.12 (0.394) N=5
	R&D Costs	**–0.78 (0.079) N=4**	**0.67 (0.073) N=5**	**0.91 (0.035) N=4**	–	0.00 (0.500) N=5
	Transaction Costs	–	–	–	–	0.27 (0.279) N=5
Techno-Organizational Barriers	Complexity	**0.80 (0.063) N=4**	0.00 (0.500) N=5	0.00 (0.500) N=4	0.26 (0.319) N=4	–
	Stage of Development	**0.91 (0.035) N=4**	0.12 (0.394) N=5	–0.40 (0.222) N=4	0.40 (0.222) N=4	0.29 (0.271) N=5
	Compatibility	0.00 (0.500) N=4	**–0.67 (0.059) N=5**	**–0.80 (0.063) N=4**	0.00 (0.500) N=5	–
	Institutional Support	0.67 (0.110) N=4	0.00 (0.500) N=5	0.40 (0.222) N=4	**0.78 (0.079) N=4**	**–0.83 (0.030) N=5**
	Testability	0.40 (0.222) N=4	**0.63 (0.077) N=5**	–0.22 (0.342) N=4	**–0.76 (0.057) N=5**	–
	Learning Potential	**1.00 (0.079) N=3**	**0.67 (0.073) N=5**	0.00 (0.500) N=4	**0.67 (0.071) N=5**	**0.80 (0.039) N=5**
	Visibility	–0.82 (0.110) N=3	**0.71 (0.054) N=5**	0.18 (0.359) N=4	0.00 (0.500) N=5	0.12 (0.394) N=5
Innovation System Potential	Antagon. Tech. Dev.	**–0.80 (0.063) N=4**	–0.33 (0.234) N=5	0.52 (0.173) N=4	**–0.67 (0.071) N=5**	**–0.75 (0.048) N=5**
	Complement. Tech. Dev.	–0.18 (0.359) N=4	**0.94 (0.016) N=5**	0.40 (0.222) N=4	**0.71 (0.060) N=5**	–0.13 (0.391) N=5
	Knowledge Prod. Pot. I	0.50 (0.240) N=3	0.00 (0.500) N=5	0.40 (0.222) N=4	**–1.00 (0.042) N=4**	0.00 (0.500) N=4
	Knowledge Prod. Pot. II	0.50 (0.240) N=3	0.20 (0.351) N=4	0.82 (0.110) N=3	–	–
	Cooperation Intrasectoral	–0.20 (0.351) N=4	0.00 (0.500) N=5	0.40 (0.222) N=4	0.50 (0.240) N=3	0.00 (0.500) N=4
	Cooperation Intersectoral	0.00 (0.500) N=4	0.35 (0.210) N=5	0.40 (0.222) N=4	**–0.67 (0.071) N=5**	**–1.00 (0.028) N=4**
	Cooperation Government	0.67 (0.110) N=4	**0.83 (0.030) N=5**	0.22 (0.342) N=4	–0.43 (0.175) N=5	0.52 (0.173) N=4
	Cooperation Science	0.67 (0.110) N=4	**0.82 (0.038) N=5**	0.22 (0.342) N=4	0.00 (0.500) N=5	0.00 (0.500) N=4

* Results hold for R3EU as well since there is only a minimal difference between the two steps which only applies to the sustainability criterion.
+ Results hold for R2BF as well except with respect to the sustainability criterion: no significant correlate was found.

technology) involves conventional technology. This is indicated by the fact that none of the systemic and organizational criteria show significant correlations. Most significant criteria are related to performance and profitability; hence 'desirability' seems to be the major determinant.

Not surprisingly, radically adjusting the country's infrastructure (R1IS, natural gas infrastructure) is one of the most problematic transition steps with respect to consent and willingness. This innovation is typically of a systemic and organizational nature. A radical infrastructural change is never desirable in itself; it is financially risky and only indirectly contributive in providing a solution to the sustainability problem. Still infrastructure is a precondition to be met but its development is more or less passively driven by other forces. It seems reasonable to accept that infrastructural shifts will on one hand strongly depend on the technological regime. Think of successful introduction of natural gas vehicles opposed to fast breakthroughs in hydrogen propulsion technology. On the other hand a more active stimulation is conceivable: a pro active strategy of a big oil company and focused government policy could provide the basis for a new infrastructure network. Still there must be a grain of confidence to start with. The important criteria for this radical transition step are institutional support, learning potential and the antagonizing and complementary technology developments.

The last transition step analyzed (I3BF, producing and blending biofuels) shows a strong resemblance with the previous one. Techno-organizational barriers and innovation system potential parameters are the determinants. An exception is the sustainability criterion which shows a strong positive significant correlation with WTP. This is a remarkable difference with the previous discussed step which is also infrastructure related but did not show a significant result for the sustainability criterion. Apparently within the biofuels discourse sustainability is considered to be an important issue. This could be an important incentive for first movers.

Discussion and conclusion

A weak point in this study is the limited number of actors interviewed. This may lead to misrepresentation of the system's constitution and render a statistical analysis problematic. The first problem can be solved to some extent by doing additional research and incorporating more actors. However, the number of critical actors is in fact limited in reality since the energy transport system is dominated by a small number of energy companies and car manufacturers. So even in an ideal situation the trouble with statistical uncertainty will persist.

Another problem is the possible incompleteness of criteria. The criteria set was formulated by aid of expert judgment and literature; its completeness cannot be assumed. Furthermore the problem of multi-colinearity among variables makes a statistical analysis rather difficult. On the other hand, our interview respondents were asked to comment on the proposed set of criteria and this did not lead us to believe that important factors were left out. The problem of criteria interdependency might be solved by making use of data reduction techniques. But then again, a larger sample size is necessary.

In order to focus our interview questions and to make comparison possible, the transition was pre-shaped by proposing two trajectories divided in discrete transition steps. Of course we should be careful not to miss valuable information. For this reason actors were asked to reflect on the effectiveness of this method and on possible alternative trajectories but in fact their views did not deviate too far from ours.

Despite the preliminary status of the project some insightful results are found with respect to the managing of transitions. However conclusions should be seen as tentative and preliminary since our findings are as yet solely related to the transport fuel system as represented in this study.

With respect to the method proposed in this paper we like to conclude that the measurement of Willingness To Participate (WTP) of individual actors for different transition steps gives a good impression of the feasibility of a transition step in terms of the shared willingness of actors to participate. The method results in a clear scheme of transition trajectories that serves as a heuristic that can be used to identify problematic steps. Our method appears to be a usable tool for quick scanning the feasibility of transition trajectories. Explaining the reasons why WTP scores deviate is more problematic.

With respect to our empirical case some interesting patterns are found. The use of hydrogen as a transport fuel is generally regarded to be a desirable future perspective where we should (eventually) strive for. Transition steps that require active effort on a relatively short term yield a larger degree of dissent than transition steps which have a short term urgency; at the same time more distant steps yield higher WTP scores. So in our case, positive WTP scores are associated with a high degree of consent.

Intermediary steps within a transition (add on technologies and hybridization technologies) are regarded as important in literature. However, our research shows that many of these intermediate steps have low WTP values and a high degree of dissent. This issue requires further research but it may shed a different light on earlier research results. The more links the chain has, the greater its potential for weakness.

The policy implications of our findings can be summarized as follows:

- Measures should be directed at facilitating consensus building for innovations on the short term;
- In case of an incremental strategy it is the automobile industry who pulls the transition; instruments are to be directed at market stimulation and deregulation;
- In case of a radical infrastructural rearrangement, government should provide incentives for change by providing finance and institutional legitimation and by organizing platforms for networking;
- A radical strategy has a lower risk for suboptimal lock-in than an incremental strategy but then large public investments are necessary and a strong top-down government policy is required;
- Intermediate steps are troublesome and do not necessarily improve transition success.

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Appendix 1: Criterion definitions and hypothetical causality relationships

Criterion	Meaning
Sustainability	A rather broad concept which was operationalized in a strictly ecological sense. Actors were asked to evaluate transition steps in terms of environmental effects like CO_2 emissions and energy efficiency effects. A positive influence on WTP is expected.
Safety	The expected customer and user safety could be of importance in deciding to invest in a technology. A positive influence is expected.
Security of Supply	The continuity of a nation's energy supply is of crucial importance in the present society. Energy supply lines can be threatened as a result of political instability. The use of alternative primary energy sources might change this situation which could influence WTP. Actors were asked to give their view on the effects of the proposed development (introduction of biofuels or natural gas) with regard to the security of supply. It is expected that the criterion positively influences WTP.
Reversibility	The risk of an involuntary technological lock-in is a threat to society in general and to the actors (investors) in particular. A transition step is considered to be more reversible if a turn-back to the starting position remains possible. Often investments in the adjustment infrastructure render this practically impossible. Actors were asked to evaluate the possibility of reversing the proposed transition step if it would turn out to be unsuccessful. It is expected that reversibility has a positive influence on WTP.
Adaptability	A transition step is considered to be more adaptable if more than one foreseeable possible end-terms can still be reached after its realization. As with the previous one, this criterion is related to the flexibility of the transition step. Actors were asked to evaluate the number of feasible alternative technological trajectories/applications if the intended development would turn out to be unsuccessful. It is expected that adaptability has a positive influence on WTP.
Profitability	A rather straightforward criterion, measured as the actor's expected financial revenues as a direct result of participating in realizing the proposed transition step. A positive influence on WTP is expected.
Performance	This criterion is only relevant with respect to innovative end-use technology. Differences in comfort and technical performance of cars could be relevant in deciding for or against participation. The relevant actors were asked to evaluate cars equipped with new technology with respect to qualities like leg space and acceleration power. A positive influence on WTP is expected.
Investment Costs	Actors were asked to give their view on the height of the expected investment costs for a transition step. The height of investment costs are expected to negatively influence WTP.
R&D Costs	Actors were asked to give their view on the height of the expected R&D costs for a transition step. The height of R&D costs are expected to negatively influence WTP.
Transaction Costs	Another term for transaction costs is talking costs or organization costs. During the interviews it turned out that few actors could relate to this concept so it was dropped. It is expected that the criterion has a negative impact on WTP.
Complexity	A more complex technology could raise difficulties with regard to maintenance and use. Most important, technology adopters (customers) could fear the new technology and withhold from participation. Actors were asked to give their perception on the complexity of the technology developed in the proposed transition step. It is expected that complexity negatively influences WTP.
Stage of Development	Developing technology is known to pass through certain stages in time along which exploration and experimentation gradually makes place for upscaling and market penetration. If the technology needed to realize a transition step is already fully developed, this decreases uncertainty with respect to the technical aspect of the transition problem. Therefore it is expected that for transition steps where the development for relevant technology is in a later stage, WTP is higher. Actors were asked to evaluate the development stage of technology associated with the proposed transition step. A positive influence on WTP is expected.

Continues .../

Appendix 1: Criterion definitions and hypothetical causality relationships, *Continued*

Criterion	Meaning
Compatibility	The fewer infrastructural adjustments are necessary, the more compatible a technology is with the current system. This clearly reduces the risk of failure of a transition step. Actors were asked to evaluate the compatibility of new technology with the old system. A positive influence on WTP is expected.
Institutional Support	For a technological system to work, factors as regulation, government support, intermediary organizations and available education programs are of crucial importance. This type of support could be considered as the necessary immaterial infrastructure of the system. During transitions this institutional framework needs to reform itself in order to sustain or control the technological developments. Actors were asked to evaluate the proposed transition step with respect to the yet available institutional framework in terms of regulation and support. A positive influence on WTP is expected.
Testability	A technology is more testable if it can be tested on a limited scale for a limited time. In this way customers and users can try out the technology in a relatively low-risk environment. Actors were asked to evaluate the testability of technology relevant to the proposed transition step. A positive influence on WTP is expected.
Learning Potential	A technology's learning potential is of importance when evaluating its chances of transcending the niche stadium of a technology. Learning effects might result in lower costs, making progress possible. Actors were asked to estimate the learning potential of technology relevant to the proposed transition step. A positive influence on WTP is expected.
Visibility	The visibility of a technology describes the degree in which it appeals to customers or users. Some changes might be technically invisible; for instance when blending biofuels with petrol, it's possible that customers won't notice this except for the price they have to pay. Other technology innovations will be more noticeable. Actors were asked to value the visibility of the technology relevant to the proposed transition. The effect on WTP is difficult to predict since negative as well as positive effects can be expected. On one hand people want to be seen using new products with a clean image, but on the other hand people are attached to certain customs and are reluctant to change their habits.
Antagonizing Tech. Developments	Technology develops in a complex environment with lots of other technological developments going on. Some of these developments could pose a threat to the success of the proposed transition step. Actors were asked to give their view on the significance of this threat. Since increased threats cause higher investment risks, a negative influence on WTP is expected.
Complementary Tech. Developments	Technology develops in a complex environment with lots of other technological developments going on. Some of these developments could be supportive to the success of the proposed transition step. Actors were asked to give their view on the significance of this effect. Since increased support causes lower investment risks, a positive influence on WTP is expected.
Knowledge Production Potential I / II	The rate in which new technology is developed is believed to depend on the general vitality of a sector's system of innovation. This vitality is sometimes measured in terms of active researchers (I) and number of patents & patent licenses (II). Actors were asked to give their view on the number of active scientists/ engineers (I) and the number of released patents and licenses (II) related to the technology necessary in the proposed transition step. If the sector appears to be strong in terms of innovative capacity, actors might feel more secure in taking investment risks. Hence, a positive influence on WTP is expected.
Cooperation • ***Intrasectoral*** • ***Intersectoral*** • ***with Government*** • ***with Science***	The development of new technology and the rearrangement of infrastructure is a complex business for which intensive cooperation between actors is a necessity. Actors were asked to judge the quality and quantity of the associations considered relevant with respect to the proposed transition step. A distinction was made between cooperation that is intrasectoral (within the same sector) and intersectoral (between sectors). Furthermore government cooperation and cooperation with the scientific/academic world was distinguished. For all types of cooperation a positive influence on WTP is expected.