Flexible transition strategies towards future well-to-wheel chains: an evolutionary modelling approach

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Abstract

Well to wheel (WTW) analyses mainly focus on alternative road fuel/vehicle systems that are very different from the current crude oil based individual transport system. A large share of WTW chains evaluated require changes in the energy source, new fuel production facilities, different fuel distribution systems and also modifications of the vehicles. An immediate transition to such a new system would be an unprecedented technological discontinuity. Historical examples of successful technological changes are characterized by stepwise transitions of subsystems. In this paper, we present a model that identifies likely sequences of stepwise transitions in analogy to the fitness landscape model in evolutionary biology. Applying this methodology allows for a dynamic interpretation of otherwise static WTW information. We show that sequences of transitions are path dependent, so that current decisions predetermine the future WTW system. We, therefore, argue that flexible initial transition steps that allow for different transition paths later on are favorable. Results suggest that improvements of vehicle technologies are most flexible if decision makers focus on decreasing WTW energy requirements. A full transition to diesel, as a first step, is advisable if WTW greenhouse gases should be reduced.

JEL classification: B52, L92, O33, Q42

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Abbreviations

CBG	Compressed biogas
CCS	Carbon capture and sequestration
CGH_2	Compressed gaseous hydrogen
CNG	Compressed natural gas
CO_2	Carbon dioxide
DME	Dimethyl ether
FCV	Fuel cell vehicle
FF Electricity	Electricity generated from fossil fuels
GHG	Greenhouse gases
ICEV	Internal combustion engine vehicle
LCG	Well-to-tank system: Large, centralized, gas-pipeline
LCP	Well-to-tank system: Large, centralized, pipeline
LCT	Well-to-tank system: Large, centralized, truck
LH_2	Liquified hydrogen
LPG	Liquified petroleum gas
MLG	Well-to-tank system: Medium, local, gas-pipeline
MLP	Well-to-tank system: Medium, local, pipeline
MLT	Well-to-tank system: Medium, local, truck
NG	Natural gas
SO	WTT system: Small, on-site
WTT	Well-to-tank
WTW	Well-to-wheel

1. Introduction

Gasoline and diesel are the dominant fuels in road transport. Their current advantage over alternative fuels is a well developed infrastructure including crude oil production, long distance transport, refining and area-wide refueling coverage. They are easy to use because of their high energy density at room temperature and are generally considered to be safe (especially compared to gaseous fuels). Altogether, this allows for transport services at relatively low costs and implies high barriers for alternative fuels to become competitive. However, there are three problems associated with a continuation of the current use of crude oil based fuels that require evaluation of alternatives. Firstly, oil is a non-renewable resource. Even though in the past discoveries of new oil fields and especially improved exhaustion methods have repeatedly extended the statistical reach of oil, there is evidence that global oil production will peak within the next decades (Bentley, 2002). Given current demand, prices are, thus, likely to increase substantially in the future. Moreover, the majority of crude oil reserves is concentrated in the politically instable region of the Middle East, implying additional supply security problems. Secondly, road vehicles are major contributors to greenhouse gas (GHG) emissions. They account for more than 20% of total GHG emission in the US (EPA, 2006) and for about 16% in the EU (EEA, 2006). Thirdly, local air pollution is still a problem even with advancements of end-of-the-pipe technologies, as technological progress has often at least partly been compensated by an increase in the number of cars and/or car use (Friedrich and Bickel, 2001). The focus of this paper is on potential technological transitions to alternative fuels (in the broad sense of not being gasoline or diesel refined from crude oil) combined with new vehicle technologies that reduce GHG emissions and energy requirements of road transport, which, therefore, require substantial changes of the current system.[1]

Alternative fuels and vehicle technologies are not per se beneficial. E.g., hydrogen used in a fuel cell is an efficient way of converting energy in a vehicle. But if the hydrogen is generated via electrolyses of water and the necessary electricity is produced with coal fired plants, overall GHG emissions and energy requirements per vehicle kilometer would significantly increase. GHG emissions could be reduced, though, if carbon capture and sequestration (CCS) technologies would be applied, but this would further increase energy requirements. Performance of alternative fuels and vehicle combinations in terms of GHG emissions and energy requirements is compared in so-called well-to-wheel (WTW) analyses,

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[1] Local air pollution can be further reduced with wide spread application and improvement of existing technologies, including particulate filters, catalytic converters, high pressure combustion and cleaner conventional fuels (e.g., with low sulfur content).

which evaluate the whole chain from the energy source ("well") to the transmission in the vehicle ("wheel"). As already indicated in the above example, GHG emissions and energy requirements are not necessarily correlated and therefore might be conflicting targets.[2] Thus, it depends on the actual preferences of the decision makers, which WTW chain is most desirable. In this sense WTW analyses are an essential tool to compare different visions of future road fuel systems.

However, their insights with respect to optimal transition strategies towards such new systems are limited. In the standard approach, WTW analyses focus on chains, which often differ from the current one in terms of the energy source, fuel processing technology, fuel distribution system and additionally also in the vehicle technology. The chains represent end states after a successful large scale technological transition. But forcing such a transition implies a technological discontinuity in the sense of Tushman and Anderson (1986), with not only high investments in new technologies, but also radical changes in the institutional environment. Thus, there are high barriers to such a fundamental change.

In this paper, we assume that future transitions in the WTW system are characterized by a sequence of transitions of parts of the chain (e.g., a modification in vehicle technology first, followed by a change in the fuel distribution system and so on), rather than by a single radical system switch. We suggest an evolutionary model that explores such stepwise transitions in analogy to the fitness landscape model in evolutionary biology (Kauffman, 1993). Future WTW systems are considered optimal if their performance cannot be improved with further steps. We show that stepwise transitions imply path dependence, so that initial steps can predetermine the characteristics of the future WTW system and, therefore, decrease the flexibility regarding possible end states. For demonstrative purpose we construct a dataset that reflects the main patterns of current WTW analyses. We approach WTW GHG emissions and energy requirements (per vehicle km) as two separate performance measures. It turns out that the optima of the two dimensions are not "close" to each other in a technological sense.

Because of path dependence, we focus our analysis on potential initial steps. We check, whether they shift the system closer to a specific optimum and apply two different measures of flexibility. One is the number of different optimal WTW systems that can be reached within a certain number of later transition steps. The second flexibility measure counts the number of different paths, i.e., different sequences of transition steps that lead to these optima. We put particular emphasis on flexibility, because information about future WTW data is uncertain. Data are derived given current assumptions about technological feasibility,

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[2] In many cases reductions in energy requirements imply also GHG emission reductions, but, e.g., GHG emission reductions from CCS always imply higher energy requirements.

technological progress and economies of scale, basically in every part of the chain. Thus, a first transition step that leaves open a wide range of future steps, as implied by the flexibility measures, can be seen as robust if, e.g., certain future WTW chains turn out to perform much worse later on than predicted now. Moreover, initial steps that improve energy requirements and reduce GHG emissions at the same time are considered preferable, because they allow for a later change in preferences. Thus, initial steps that move the system closer to the optima in both dimensions and allow from thereon reaching the optima on many different paths, can be interpreted as being most flexible and, therefore, having a low regret potential. We find that changes in vehicle technologies are most flexible if reductions of WTW energy requirements are addressed. If the focus is on GHG emission reductions, a general switch from gasoline to diesel appears to have the lowest regret potential, as many different paths later on lead to an emission optimum.

In the next section, we show how stepwise transition can lead to path dependence and lock-in into suboptimal systems. In section 3, we suggest a decomposition of the WTW chain into subsystems, constituting the so-called design space of WTW chains. Thereafter, section 4 describes the dataset we constructed for demonstrating the potentials of the approach. In section 5, we present results and we conclude in section 6 with pointing out limitations of the current study and provide recommendations how to improve future WTW studies.

2. Stepwise transition and path dependence

Implementation of one of the chains that are usually evaluated in WTW analyses would often require a radical departure from today's technologies along the whole chain. However, historical examples show that successful technological transitions can often be characterized by sequences of (using the terminology of Henderson and Clark (1990)) "incremental innovations", i.e., changes of subsystems rather than single "radical innovations".[3] In the context of WTW chains, an example for an incremental change is the introduction of unleaded gasoline during the 1980s, which was required by cars equipped with a 3-way-catalytic converter. Existing distribution systems, pump technologies etc. could be used; and a major advantage for its fast penetration of the market (in many countries way ahead of the cars with

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[3] Classifying technological change to be incremental or radical is similar to Dosi's (1982) differentiation between change along the same "technological paradigm" and emergence of a new paradigm. A discussion of these evolutionary views of technological change in the context of environmentally friendly products can be found in Kemp (1994).

3-way-catalytic converter) was that most conventional engines could also run on unleaded gasoline, so that the innovation was fully compatible with the existing system (Westheide, 1998). In contrast, the introduction of hydrogen as an alternative fuel would be radical, as it requires several changes in the whole fuel production, distribution, and end use system at the same time.

Given the size of the WTW system, "incremental changes" actually already imply huge investments and we, therefore, refer to them rather as transition steps. We argue that the investments necessary for making transition steps will not achieve public acceptance if they do not improve the overall performance of the WTW chain. This notion of stepwise transition can be described in analogy to the fitness landscape model in evolutionary biology (Kauffman, 1993). The fitness of an organism, in a Darwinian sense, depends on the combination of genes in a genotype. Correspondingly, the performance of a WTW system is given by the combination of subsystems, such as fuel production or vehicle technology. The fitness of an organism changes through mutations of its genes, while WTW system performance is altered by a transition step that changes a subsystem. According to evolution theory, a mutation is only selected (e.g., by survival) if the new combination of genes has a higher fitness.[4] If a fitness value is assigned to each sequence, a (multidimensional) "landscape" with peaks and valleys results (see Figure 1 for a three-dimensional example). The peaks are the optima (global or local) in a fitness landscape and are defined by the fact that any mutation implies a lower fitness value, i.e., no further mutations will be selected. Describing technological developments in analogy to evolutionary processes becomes increasingly popular (Kauffman, 1993; Ziman, 2000; Frenken, 2006). We follow the established terminology by interpreting all possible future WTW chains as the technological "design space" (Bradshaw, 1992) of an alternative fuel system.

Stepwise transition in the WTW chain may actually lead to a lock-in in a local optimum. A transition towards a local optimum cannot be reversed, as this would imply a decrease in performance (combination 111 in the example in Figure 1). This means that the whole transition process is characterized by path dependence, i.e., early decisions can predetermine potential end states.[5] An example of path dependence in Figure 1 is when a designer starts

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[4] As an example, lets assume that an organism has the following sequence of genes 1 0 1 0 0 (i.e., the genotype) with a fitness of A. Its offspring now appears to have a sequence 1 1 1 0 0 with fitness B. If B > A the offspring is "fitter", will survive in the selection environment and might reproduce. But if B < A the offspring will die before reproduction. Note that this mutation/selection process corresponds to a trial and error (random) search, while a technological transition step would be a controlled decision.

[5] Note that this notion of lock-in into local optima is static, in the sense that the performance levels are inherent to the technology. This is different from lock-in phenomena due to increasing returns to adoption, as initially described by David (1985), Arthur et al. (1987) and Arthur (1989).

from string 010 and the first transition leads to string 000, and the second transition to the globally optimal string 100. However, when search starts again in 010, but the first transition leads to 011, the only remaining possible transition will inevitably lead to the local optimum 111.

3. The design space of WTW chains

3.1. Five subsystems

Complex technological systems generally contain several semi-independent subsystems (Simon, 1969). Each subsystem has certain specifications and the performance of the overall system depends on the combination of the specifications. All theoretically possible combinations form the design space of the technological system. Analyses of technological developments in the past show that successful improvements are often characterized by detecting new combinations of already existing specifications. Examples are early airplanes (Bradshaw, 1992), wireless telecommunications (Levinthal, 1998) and the development of steam engines (Frenken and Nuvolari, 2004). These evolutionary dynamics are well captured by the combinatorial nature of a design space and by having innovation be represented as a move in this design space.

The decomposition of the WTW chain into subsystems involves some degree of arbitrariness and is therefore debatable. As a first approximation for this study, we suggest a rather high aggregate level as shown in Figure 2. We define the initial energy source (the well) as the first subsystem, which may include extraction, initial cleaning processes, transport to the conversion site etc. We consider seven different sources, i.e., this subsystem can have seven different states. We include all different fossil fuels (crude oil, coal and natural gas) as a direct source or in an energy mix for producing electricity (implying hydrogen production via electrolysis later in the chain). Under “biomass” we subsume a variety of agricultural sources, such as wood, straw, rapeseed and so on. We do not differentiate between them (even though differences can be substantial), because we wish to analyze all sources at a similar level of aggregation. Non biogenic waste (also referred to as municipal waste) can be seen as an indirect use of fossil fuels, too, but at low costs, as it is assumed to be generated anyway. We included wind power as a representative for all (non biomass) renewable energy sources, which are characterized by high investment costs and low operating costs.[6] Nuclear is not evaluated, because intensified use for car fuel production seems to be an unrealistic option, given perceived hazardousness and the unsettled problem of long term radioactive waste storage.

Second, we allow for a binary choice whether to apply CCS during the fuel processing or not. This implies the assumption that there are sufficient sites for dumping carbon dioxide available.

Third, we differentiate seven combinations of production scale, location of production, and distribution to the filling stations. We combine these measures, because they are not fully independent. Applying fuel processing in large scale facilities requires centralized production, and, therefore, implies rather long distances to filling stations that must be covered by either pipelines or trucks. Medium scale production would be on a local level with rather short distances to the filling stations. The distribution system (pipeline, gas-pipeline or truck) could be modeled as a separate subsystem, but since we also want to consider onsite fuel production, which basically does not require any additional alternative fuel transport infrastructure, we grouped scale, location and distribution system to seven mutually exclusive options.

Fourth, we include nine different car-fuels covering almost all options that are currently considered as potential medium to long term substitutes for gasoline. Note that only for a few combinations the well to tank (WTT) part we described so far is really a chain with successive steps as indicated by Figure 2.[7] In most cases, the chain should be read, e.g., as "generating compressed gaseous hydrogen (CGH_2) in a large, centralized facility, with CCS, and distributing it with trucks."

Fifth, and finally, we separate three vehicle types, conventional internal combustion engine vehicles (ICEVs), Hybrid-ICEVs, which combine an ICE with a battery allowing for regenerative braking, and fuel cell vehicles (FCVs). The FCVs are required to have an onboard fuel reformer if not fueled with CGH_2 or liquid hydrogen (LH_2) and are also assumed to be "hybrids" by having a battery for regenerative braking.

Even for the high level of aggregation with only five subsystems, there are $7 \cdot 2 \cdot 7 \cdot 9 \cdot 3 = 2646$ theoretical combinations of energy sources, CCS, scales/distribution systems, fuels and vehicles. These combinations form the design space of the WTW system. There are three different measures of the overall performance that are usually estimated for each combination:

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[6] Fuel production from wind power can follow variability of wind. This is an advantage over wind power fed into the grid, which must be backed up with conventional power generation due to the lack of efficient large scale electricity storage options.

[7] An example for a chain that actually follows the structure is: NG → no CCS → small, onsite → CGH_2.

WTW energy requirement per km driven (or similarly WTW energy efficiency), WTW GHG emissions per km driven and local vehicle emissions. Even though local emissions are an important decision parameter, we do not investigate them further, as they are mainly determined by (future) end-of-the-pipe technologies or are absent if hydrogen fuels are applied. With respect to the other two performance measures, almost 2/3 of the combinations would never be seriously considered, as, e.g., generating gasoline with wind power or transporting LH_2 in pipelines over long distances, given that liquid hydrogen must be cooled to less then 20 Kelvin. Such combinations are excluded from the analysis.

3.2. Design space search

In the simplified WTW system the (dominant) current state is represented by gasoline refined from crude oil without any carbon scrubbing in large scale facilities. Trucks are responsible for delivery to filling stations and the cars have internal combustion engines. From that starting point, there are theoretically 23 different first transition steps possible (six in sources, one regarding CCS, six in distribution, eight in fuels and two in vehicles). The definition of a design space requires that the subsystems are fully technologically independent, i.e., one part in the chain may change without requiring any modifications at other parts of the system. This does not hold in a strict sense. A change from gasoline to methanol, for example, requires modifications in the ICE or the reformer of the FCV (depending on what vehicle type is applied when the fuel is switched). We assume, though, that necessary adjustments in other parts of the chain are negligible compared to the major commitment that a change in the state of a part implies in general. This leads to another necessary assumption regarding switching costs. The current debate about alternative fuels puts strong emphasis particularly on necessary infrastructure costs. If we were to address switching costs, we would theoretically require data for a switch from each chain to all different other chains with the (impossible) task to estimate switching costs from one future system to another future system. We refrain from including switching costs and assume that a transition step is an extremely costly and thus rare event. When evaluating different initial steps with respect to flexibility later on, we analyze no more than four further future transition events, because we just want to allow all five subsystems to be potentially changed (even if it is also possible that more than one transition occurs in the same subsystem).

4. Construction of the data set

A large share of the theoretical transitions actually implies dramatic increases in WTW GHG emissions and WTW energy requirements compared to the current system. This problem that is due to the technological dependence between subsystems can be handled in the model by simply assigning an extremely low performance level, so that no transition path can lead through this combination of subsystems. In terms of the fitness landscape metaphor, these options represent the valleys in the landscape. This actually holds for many of the 23 different initial first transition steps (e.g., switching directly from crude oil to wind power). After "eliminating" WTW systems in that way, 987 chains remained to be evaluated in terms of energy requirements and GHG emissions. To gather the necessary data, we screened the most recent WTW analyses available (GM et al., 2002; Ahlvik and Brandberg, 2001; EC-JRC, 2006), which cover a broad range of energy sources, car fuels and car technologies. Moreover, there are several studies available that focus on particular energy sources as, e.g., biomass (Delucchi, 2003) or NG (Hekkert et al., 2005). Others address pathways to particular car fuels, especially LH_2 and CGH_2 (Wang, 2002; Lipman, 2004; Ogden et al., 2004), certain car technologies (Lave et al., 2000) or the fuel supply side as a whole (MIRI, 2004). Thus, there seems to be sufficient data available. However, a large part of the data is redundant in the sense that the majority of studies evaluate the same WTW paths, which are considered most interesting with respect to long term environmental performance or most likely, given short term feasibility. But the remaining different chains cannot be merged into one data set, because they lack comparability for several reasons. In general, studies differ in their application area. Countries or regions are different in their availability (and therefore costs/efficiency) of different energy sources. They vary in the distance to oil or gas fields, the size of farm land that could be used for biomass production or the amount of off-peak electricity available for electrolyses and so on. Besides these geographic characteristics, differences may also arise from the driving pattern (number of cold starts, average speed etc.) or the efficiency of the current car fleet as a benchmark. These region specific variation in results is inherent in the research questions the studies address and can, therefore, be considered inevitable. But sources of divergence lie also in the assumptions with respect to future efficiencies of the technologies applied in each part of the chain.

To achieve the highest possible consistency in the dataset, we take the EC-JRC (2006) as a starting point, because it offers the widest range of different WTW chains. It reports an estimate for WTW GHG emissions and WTW energy requirements per 100km traveled. With the exception of wind power (where variable costs are basically zero), the latter can be used as a proxy for the required resource amounts and therefore the implied operating costs of the fuel system.[8]

For missing chains that are available from other studies we use comparable chains as reference points (e.g., basically all studies provide data on a chain with FCVs fueled by CGH_2, which is generated from large scale natural gas steam reforming) and then compute the relative difference to the reference point. If missing chains are also not available from other studies, we take data from the most comparable chains available. For example, several non biogenic waste chains (without CCS) are derived from biomass chains assuming a slightly higher energy requirement for the waste processing.

Given the data in EC-JRC (2006), CCS can be applied to basically all chains, however, for distributed and particularly onsite fuel production we put a high penalty, because it implies maintaining a widespread CO_2 pipeline system. The changes in environmental benefits and also the energy requirements depend mainly on the amount of carbon that can be sequestered. For example, according to EC-JRC (2006) if coal is used for H_2 production, huge amounts of carbon can be captured (WTT GHG emissions, which are equal to total WTW emissions in the case of H_2 go down by 80%), but only with high additional energy input (+27%). But in a gas to liquid production of synthetic diesel, the majority of carbon remains in the fuel, so that WTW GHG emissions are reduced by only 13% requiring 9% more energy at the WTT side. When assigning available data to missing values by making percentage changes, we differentiate according to the process as “hydrogen” or “non-hydrogen”, “coal based”, “gas to liquid”, “liquid to gas” etc. Increases in energy requirements are in the range of 5% to 25%, while decreases in GHG vary within 5% to 80%, however, the vast majority of changes are at the low end of theses ranges.

Differences in scale are jointly addressed with differences in the distribution system. For several chains there are offsetting effects. For example, producing hydrogen from natural gas at a decentralized medium scale requires less energy compared to the large scale option, but, on the other hand, the hydrogen is already closer to the end use at the filling station. In the WTW chain, we relate differences in distribution costs to the fuel. We assume that the bulk of transportation costs/energy requirements associated with the energy source is inherent to the

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[8] The costs of a feedstock vary of course. However, if the use of a rather cheap resource implies high energy use per km, then opportunity costs are high, because it might be more profitable (in terms of energy service per unit of resource) to use the resource for other energy generation rather than car fuel production. But for wind power energy (cost) estimates remain arbitrary. With respect to GHG, though, its environmental benefit for fuel production can be assessed with alternative uses, e.g., the replacement of fossil fuel based electricity production (EC-JRC, 2006).

source option itself (e.g., homegrown biomass vs. imported natural gas), so that further distribution to the fuel production sites can be neglected. Given the changes in costs and GHG emissions reported in NRC (2004) and Lipman (2004), differences from the best to the worst (feasible) production scale and distribution system do not exceed 25% (for non-onsite production systems).

As the data refer to energy requirements and GHG emissions per 100km traveled, the vehicle efficiency directly affects the WTT values. For the few cases the EC-JRC (2006) data is not available for different car types, we use the efficiencies reported by Ahlvik and Brandberg (2001).

Instead of taking the actual values (energy requirements in MJ/100km and GHG in grams of CO_2equivalents/km), we applied a monotone transformation to a 0 to 100 scale for energy requirements and a -30 to 100 scale for GHGs; and we round to integers. The reason is twofold. Firstly, we want to point out that we applied several (ad hoc) assumptions to create the dataset that prevent us from having precise point estimates. Secondly, the scaling shifts the focus to a more qualitative measure (better or worse performance), which is decisive in the methods we apply.

We also know that uncertainties associated with the WTW data from different data sources are high. Even estimating a simple index, like the one used so far, can be considered as rather ambitious. In the following, we will, therefore, present also results for an even less precise measurement. Instead of rounding to an integer index, we round to a multiple of five.

We depart from the EC-JRC (2006) methodology in that "negative emissions", i.e., reductions of atmospheric CO_2, can only occur using biomass together with CCS. EC-JRC (2006) reports negative emissions also for fuel processing from municipal waste. But the negative emissions are then only due to the improvement relative to the current practice of waste burning. We, therefore, assume that in a "CCS world" alternative use would also imply CCS. Moreover, in the case of biomass, we assume that negative emissions arising from hydrogen production are independent from vehicle technology. In EC-JRC (2006), CO_2 reductions are particularly high if hydrogen is used in an ICEV. Efficiency of ICEVs is low, i.e., they require more fuel and therefore imply more biomass production, so that a higher amount of carbon can be sequestered. In our approach, this would imply that in a biomass/CCS chain no switch to more efficient vehicles would be made according to GHG emissions. We circumvent this peculiarity by addressing the same negative emissions also to the more efficient Hybrid-ICEVs and FCVs. Thus, we indirectly assume that the same amount of biomass is produced. The share that is not required for fuel production would then substitute fossil fuels in electricity production.

Figure 3 and Figure 4 provide a notion of the data used in the model. Figure 3 plots a selection of the feasible chains grouped by the different sources, with and without CCS. The large triangle identifies the state of the current system. Note that chains with identical values are plotted on top of each other, so that differences might be exaggerated. However, some general patterns can be identified that most WTW analyses have in common. With respect to GHGs, the majority of chains performs better than the current system, where natural gas based chains are only slightly better and biomass chains, particularly with CCS, perform best. Most of the chains, which are worse, generate fuels from coal or fossil fuel based electricity. In terms of energy requirements, the current system performs quite well. One might expect chains with wind power to have basically no energy requirement (and, therefore, no emissions). But here, only the fuel production is assumed to be generated by wind power, but maintenance, and hydrogen distribution and storage still requires conventionally produced energy.

In Figure 4 chains are plotted according to the car fuel. The large square refers to the current gasoline chain. Note that most fuels are to some degree gathered in certain “areas”, but the hydrogen chains seem to be “all over the place”.[9] Together with Figure 3 it can be seen that the hydrogen chains perform well (in both dimensions) if produced from biomass and perform worst if produced from fossil fuel based electricity.

5. Results

5.1. Description of optima

We define a (local) optimum as a combination of five subsystems for which holds that any further transition in any subsystem leads to a decline in performance, which in the given context translates in an increase in the WTW energy requirement index or the WTW GHG emission index respectively. As the indices are rounded to integers, chains with identical performance occur. Thus, optima can consist of more than one chain, which are "neighbors" in the sense that they are no more than one transition step away from each other.[10] We refer to the number of neighboring chains within an optimum as the size of it.

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[9] For the sake of clarity we left out methanol, DME and LPG, which are basically in the same “area” of ethanol and CNG/CBG.

[10] In the notion of a fitness landscape such optima would represent a "plateau" in case of a maximum and a "plane valley" for a minimum.

Table 1: Optima of WTW performance measures contains a full list of the optima in the WTW design space. In the WTW chain with lowest energy requirements CGH_2 is generated from crude oil without CCS at a large scale.[11] The most energy efficient use of hydrogen is in a FCV. Distribution to the end use is indifferent (given the precision of the data) between truck and gas-pipelines, so that the optimum is of size two. There are two local optima, i.e., suboptimal chains that would be end states of a transition process. In local optimum *A,* wind power is used to generate LH_2. The second local optimum (*B*) contains basically all natural gas (NG) to compressed natural gas (CNG) paths. As "compression" is the main fuel procession, scale and distribution is of minor relevance. Note that burning CNG in a Hybrid-ICEV is more efficient than using an FCV with an onboard reformer.

Turning to GHG emissions, the use of biomass together with CCS implies the highest emission reductions and is therefore optimal. As discussed above, reductions occur (by assumption) independent of the vehicles type. A simple measure for the distance between two chains is the so-called Hamming distance, which denotes the number of transitions necessary to get from the one chain to the other.[12] Applying this measurement, the GHG emission optimum is at least three transition steps away from the global energy optimum and at least two steps from a local optimum (*A*).[13] Given that the maximum distance is 5 and one transition step implies a major technology shift, we conclude that the two performance measures are conflicting targets not only with respect to CCS, which is generally more energy intensive. A transition driven by energy requirements would therefore look very different from a transition driven by GHG emissions.

As explained, we also analyzed the data using a rounding to a multiple of five. As we can see from Table 2 not surprisingly, the optima become larger. The global optimum and local optimum *A* are now merged, because new connections of one step transitions come into existence, which have the same performance of 20. Due to the rounding, the local optimum *B* is now also part of the global optimum (performance of 20), but the NG/CNG based chain still remains separate.

The global GHG emission optimum is also larger for the less precise measurement, because CGH_2 and LH_2 chains become equivalent. According to the Hamming distance, the GHG

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[11] Note that EC-JRC (2006) does not provide any crude oil to hydrogen chain information. The index values here are computed using the (MIRI, 2004) data which imply a conversion to naphta first. Thus, we cannot rule out that the high performance of these chains might be due to problems of merging different data sources.

[12] The concept also originates in biology to measure the genetic difference in a genotype space (Kauffman, 1993).

[13] The distance here depends on the direction of transition. To get from local optimum *A* to the GHG emission optimum takes three steps (changing the source, CCS and scale/distribution). The other way around, CCS becomes obsolete in the special case of wind power and should therefore not be counted; but the distance increases, if the vehicle type must also be switched.

emission optimum gets close to the energy optimum *A*. The difference is reduced to the application of CCS (given that CGH_2 is generated in large scale centralized production with truck distribution and used in FCVs). Thus, a transition based on energy requirements targeting into the direction of optimum *A* leaves open the option to get also close to the emission optimum. Conversely, getting into optimum *B* leaves the emission optimum far away, even in the less precise measure.

5.2. Flexibility of first transition steps

In the previous section, we described potential end states of transition processes. Now, we turn to the transition itself. Figure 5: Example for an emission reducing transition to the GHG emission optimum shows, as an example, one potential stepwise transition from the current WTW system to the optimum with respect to GHG emissions. It is derived in a backward approach applying the knowledge about the characteristics of the optimum. Note that during the whole transition process, each transition step is required to raise performance. The first step is the general substitution of gasoline by diesel. In a second step, Hybrid-ICEVs displace conventional ICEVs. Thereafter, diesel is not refined from crude oil anymore but synthesized from biomass. In the fourth step, the then existing biomass production for fuel generation is used to produce LH_2 instead of diesel.[14] Finally, the most significant emission reduction step is made by introducing CCS. In the example, GHG emissions strictly decrease in each step. In general, we allow transition steps to be taken, even if performance remains unchanged, so that bridging steps that lead to improvements later on are possible.

In contrary to the successful transition process based on knowledge about the optimum, Figure 6: Example for an emission reducing transition following a myopic decision rule provides an example of a transition following a myopic decision rule. The rule applied forces a change in every subsystem, starting with the energy source, followed by CCS, and so on. Always the best alternative is selected. There is no energy source available that performs at least equal to crude oil at the beginning, so that the energy source remains unchanged. Then, gasoline is substituted by CGH_2 (for reasons described in footnote 14), CCS is applied and a possible switch to a gas pipeline system is made (at the same emission level). Finally, FCVs are introduced. During the transition, emissions are reduced just to an index value of 3 compared to the -26 in the optimum. If the decision rule is changed in order to start with a

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[14] An ICE running on diesel (or other hydrocarbon fuels) not only emits CO_2 but also methane and nitrous oxide which have a high climate forcing. These emissions are abated if hydrogen is used as a fuel. Since energy input is not considered in this transition path (energy input for LH_2 production and distribution is substantially higher than for diesel, but is generated from emission neutral biomass), it is, therefore, beneficial to switch to hydrogen.

possible change of fuels instead of the energy source, the fifth transition step would allow for a change to biomass. This would lead to an emission index of -22, which is still suboptimal. Thus, myopic transition strategies should be rejected. Specific ones might actually get to the optimum within five steps, but they would do so, if at all, by chance.

We argued above that making a transition step might take up to a decade. Thus, managing the transition process beyond the first step can hardly be framed in a credible policy. Moreover, within that time horizon, technological development, new information about WTW chains or changing preferences is likely to prove the original transition plan obsolete. Nevertheless, decisions about the first step have to be made given today's information. This implies that a first transition step should move the system closer to what we now consider an optimum. Table 3 shows the shortest paths to the optima implied by all potential first transition steps, and the values in brackets refer to the average performance index value along the path. Initial transitions that lead to an increase in GHG emissions and energy requirements are excluded. Transitions that are emission reducing but require more energy are marked with a (-). There are only four transitions that are emission reducing and energy efficiency improving, which are a change to a pipeline distribution system, a general replacement of gasoline by diesel and changing vehicle technology to Hybrids or FCVs (which would initially require an onboard reformer). These four potential transitions would not be regretted if there is a later change in objectives towards emission or energy optimization.

If the focus is on WTW energy requirements at the beginning, a switch to FCVs with onboard reformers requires just one more step to reach the global optimum, so that the length of the shortest path is two. That switch is also flexible in the sense that the two other (local) optima are still reachable if, what is now perceived as the global optimum, later on turns out to be technologically (or economically) infeasible.

Moreover, the average energy requirements along the paths to the optima are always lowest compared to the other potential first switches. An initial switch to Hybrid-ICEVs has similar characteristics, but shifts the system one step closer to the local optimum *B*.

Currently, car manufacturers seem to favor direct hydrogen vehicles over onboard reforming technologies. A major problem has been to reform sufficient amounts of hydrogen "on demand" for acceleration. However, the latest FCV prototypes are "hybrids" having also a battery, so that a smaller fuel cell could run with a constant amount of hydrogen reformed. Thus, we consider reformer FCVs to still be a valuable option.

If emission reductions are the center of attention, those switching options that move the system close to the optimum (switch to CCS or switch to CGH_2) and the one with the lowest average emissions during the transition (switch to LH_2) directly imply a significant increase in energy requirements.[15] In that respect, they are inflexible and have a high regret potential. Out of the remaining switching options changing vehicle technology also performs best with respect to distance to optimum and average emissions along the transition path.

After the first transition step is made, new information about the performance of specific WTW chains might become available. In a risk averse setting, it would be desirable to have transitions that are flexible in case of "bad surprises". In the transition example of Figure 5: Example for an emission reducing transition to the GHG emission optimum a (hypothetical) "bad surprise" would be that after the first two transition steps it turns out that large scale biomass production to generate synthetic fuels does not decrease GHG emissions as much as expected, so that the emission index of all biomass chains must be increased by, say, 10 units. Then, the optimum remains optimal (-16), but the switch to biomass (3rd step) could not be done anymore, because it implies an increase in emissions (from 33 to 28+10 = 38).

As a benchmark of how vulnerable the transition path are to such "bad surprises", we compute the actual number of paths that lead to an optimum, given the initial transition step. We only look at transitions, which are not longer than 5 steps; so that all parts of the chain could be altered once (five transitions already imply a time horizon of some 25-50 years)[16]. This measurement can only be interpreted in relative terms, because it depends on the construction of the dataset. Including more different (realistic) options in the subsystems or increasing the number of subsystems is likely to raise the absolute number of potential paths (and vice versa).[17] The results are shown in Table 4. If GHG emissions are optimized, replacing gasoline with diesel offers the highest number (59) of different paths to get to the optimum. Of those options, which also lead to reduced energy requirements, the second most flexible one is the switch to Hybrid-ICEVs with only a bit more than half as many different paths (32), followed by the switch to FCVs with reformers (22). Changing to pipeline distribution predetermines a single transition path of 5 steps (see Table 3) and can, therefore, be considered extremely risky.

If transition steps are evaluated according to energy requirements, changing vehicle technology offers the most paths towards the global optimum. It is noticeable that, no matter

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[15] The first step of switching to hydrogen produced from gasoline hardly reduces GHG emissions. Zero TTW emissions slightly compensate for higher WTT CO_2 emissions implied by higher energy requirements for production, storage and distribution of hydrogen. The overall change in emissions is well within the range of data uncertainty, so given the unquestionably higher energy demand, we consider the two options unrealistic.

[16] However, in most potential transitions, certain parts of the chain are changed more than once leaving others unmodified.

[17] A potential normalization would be a division by the number of feasible transition paths to the optima, but that number would also be subject to specific characteristics of the system set up.

which first transition is made, there are much more potential paths towards the global optimum than to the two local optima. This can be interpreted as an indication that chances of a lock-in in a suboptimal system due to current decisions are rather low.

To sum up, the optimal initial switch depends on the relative importance of the objectives. Changes in the vehicle technology are favorable with respect to energy requirements in terms of flexibility, shortness of distance to the optima and average energy requirements over the shortest transition path. We conclude that they have, therefore, the lowest potential regret. Only if the focus is on emission reductions and flexibility alone, the general switch to diesel becomes the best option.

In Table 5 and Table 6 we provide the same type of results for decreasing resolution to five units (high uncertainty). Then, more chains become equivalent, so that the optima become larger and the number of paths to get there increases. Furthermore, more first step options (of equivalent performance to today's chain) arise, namely changing to medium scale refining with pipeline or truck distribution. Theoretically, LPG can be generated from crude oil, but we do not evaluate that option, because it requires more energy.[18] The pattern in the results is not different from the one reported before for the values with higher precision. In the previous section, we argued that the global energy optimum *A*, which is a merger of the previous global optimum and the local optimum *A*, is closer to the GHG emission optimum (compared to optimum *B*) and might, therefore, be preferable. All initial transitions move the system actually closer to optimum *A*, and in any case, there are much more different paths leading to it, so that chances are much higher to end up in the preferred optimum. Changes in vehicle technology are still most flexible and have the lowest average performance values along the (shortest) paths. A switch to diesel remains most appealing if the focus is on GHG emissions and flexibility. The fact that these patterns remain, even if precision is decreased substantially, indicates robustness of results.

5.3. Win-win transitions

In addition to transitions either driven by emission reductions or by reductions of energy requirements we also analyzed win-win transition steps, which increased performance in one dimension without decreasing the other one (i.e., dominant strategies). We find that all three energy optima can be reached with no more than five win-win steps. Table 7 shows the number of win-win transition paths to the energy optima. With 16 (at the global optimum), 5

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[18] Note that LPG production from crude oil is listed because it does not increase GHG emissions beyond the five unit interval.

(at local optimum *A*), and 22 (at local optimum *B*) GHG emissions remain high, at least compared to the GHG optimum (-26). In that respect, local optimum *B* can be considered worst. In general, the GHG optimum is infeasible, no matter how many transition steps are made, because reaching the GHG optimum requires a switch to CCS at some point. That switch cannot be made "win-win", as energy requirements increase.[19]

Table 7 demonstrates that there are only three potential initial transitions that allow for a win-win transition to the energy optima later on. Moreover, the first step predetermines, which optimum will be reached later on. The extreme case is switching to Hybrid-ICEVs at the beginning. Then, local optimum *B* is the only energy optimum that can potentially be reached.[20] We conclude that path dependence is much stronger if transitions should be win-win and switching to FCVs or diesel would then be most flexible with respect to number of optima and the number of paths to the energy optima, especially to those with lower emissions. This implies that a government policy that requires all decisions concerning transitions to be beneficial for both energy requirements and GHG emissions is not desirable. There are important trade-offs between the two performance measures, and trying to satisfy both at the same time in all transition steps may be too ambitious and too risky in terms of irreversibilities in technological development.

6. Summary and conclusions

Transitions in complex technological systems have been previously analyzed in analogy to mutations of genes that enhance the fitness of an organism. In this paper, we apply this methodology to potential future changes of the WTW chain in individual transport. WTW chains can be interpreted as a complex system in terms of the analogy, because they can be described by two necessary characteristics. Firstly, the WTW system contains subsystems that can change independent of the other subsystems, and secondly, the overall performance of the system depends on the combination of states of the subsystems.

WTW studies usually compare WTW chains, which represent end states after a successful system change. But simultaneous transitions to a different energy source, different fuel production and distribution system and different vehicle technology would be a technological

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[19] If precision is decreased the GHG optimum becomes feasible, because for some subsystem combinations the increase in energy requirement due to CCS is within the five unit rounding.

[20] This does not mean that all later win-win transitions will actually get to that optimum. We actually find that most transitions end in a system with higher than optimal energy requirements and emissions way above emission optimum.

discontinuity, which bares a lot of uncertainties and is, therefore, unlike to happen. We argue that a stepwise transition described by successive changes in subsystems of the WTW chain is in better accordance with what has been observed historically in other technological transition processes (Levinthal, 1998; Frenken and Nuvolari, 2004). We assume that steps will only be taken if they reduce GHG emissions or energy requirements (as a proxy for operation costs) over the whole WTW chain. Which criterion matters, depends on preferences of decision makers. But stepwise transitions imply path dependence of the system and the potential existence of local optima. In the data, we find local optima with respect to energy requirements, which would be end points of transition processes. With respect to GHG emissions, we find only one global optimum. Knowledge of the optima makes it possible to identify successful transition paths, which might be undetected if myopic transition rules were applied.

We compare the different energy optima according to their distance to the emission optimum, where distance is denoted by the number of necessary transition steps to get from one optimum to the other. We find that a (local) energy optimum characterized by NG/CNG is particularly far away from the emission optimum. Thus, a transition that is initially driven by energy optimization could end there. If then, later on, GHG emissions are considered more important, it would be particularly expensive to decrease emissions.

The main focus of our analysis of potential transition paths is on flexibility. One transition step is not only extremely costly, but is also likely to take up to a decade. Thus, after this period, new information (and technologies) will probably be available, and even preferences of decision makers might shift. Therefore, it is favorable if the initial transition step does not predetermine the later transition path, but allows for alternatives. We find that changes in vehicle technology are most flexible if the initial focus is on energy requirements, suggesting that R&D efforts should focus on the vehicle subsystem in the short term. Moreover, the GHG optimum remains feasible if a later shift in preferences occurs. If GHG emissions are the center of attention right from the beginning, a replacement of gasoline by diesel appears to be most flexible. We also look at what we call win-win transitions that decrease GHG emissions without increasing energy requirements (or vice versa). In those cases, the initial decision becomes critical, as it might actually fully predetermine the later end states of the transition.

The advantage of our approach is that it allows making dynamic interpretations of existing (static) WTW information. Given substantial uncertainties related to future energy systems, policy makers are particularly interested in current transition steps that have low regret potential by being flexible. The method is simple and can also be applied to more complex

WTW systems containing any number of subsystems. More (smaller) subsystems would allow for a more detailed transition analysis, as, e.g., more than one subsystem may change within one transition step.[21] A higher number of subsystems implies an exponentially higher number of theoretical combinations (and, therefore, greater data requirements). Such a detailed analysis might, thus, be appropriate only for a subgroup of WTW chains. A subgroup with particular policy relevance would be biomass-biofuel pathways.[22] Different biomass sources, fuel conversion technologies, and so on can be distinguished. Initial paths might be preferred that allow for more different fuels later on, given the uncertainties in vehicle technology development.

The methodology we present also has its limitations. We ignore investment costs for the transition steps, so there might be trade-offs between transition costs and flexibility. Besides this general problem, there are several issues that need to be addressed in future research that qualify the results as preliminary. We interpret energy requirements as a proxy for variable costs of a WTW chain. This works sufficiently well only for those energy sources that use a feedstock as a costly input, but a direct cost estimate would be preferable. The data we use is only for demonstration purpose. It combines information from different studies with different assumptions and foci. Thus, data uncertainty is very high. We address uncertainty by deriving results for different degrees of precision and find that the general patterns of results remain. Nevertheless, a reestimation of the dataset using a single consistent WTW framework is indicated as welcome.

To facilitate evaluation of transition strategies, it would be beneficial if future WTW analyses would not only focus on the comparison of potential end states of complete transitions, but also look at chains that are likely to be intermediate steps (usually less efficient than the end states). In terms of flexibility, particularly interesting intermediates are those that are to a large degree compatible to the current system and do not predetermine the likely final state of the transition process. The results presented in this paper indicate that FCVs with onboard reforming might be a crucial technology in that respect.

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[21] We didn't allow for that in the current chain with just five subsystems, because this would correspond to a radical system switch that we consider unlikely.

[22] Several EU countries have specified targets for the share of biofuels within all fuels for automotive applications.

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References

Ahlvik, P., Brandberg, A., 2001. Well-to-wheel efficiency for alternative fuels from natural gas or biomass. A report for the Swedish National Road Administration. http://www.vv.se/publ_blank/bokhylla/miljo/lista.htm.

Arthur, W.B., Ermoliev, Y., Kaniovski, Y., 1987. Path dependent processes and the emergence of macrostructure. European Journal of Operational Research 30, 294-303.

Arthur, W.B., 1989. Competing technologies, increasing returns and lock-in by historical events. Economic Journal 99, 116-131.

Bentley, R.W., 2002. Global oil & gas depletion: an overview. Energy Policy 30, 189-205.

David, P., 1985. Clio and the economics of QWERTY. American Economic Review Papers and Proceedings 75, 332-336.

Delucchi, M., 2003. A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. Institute of Transportation Studies (University of California, Davis), UCD-ITS-RR-03-17, http://repositories.cdlib.org/itsdavis/UCD-ITS-RR-03-17.

Dosi, G., 1982. Technological paradigms and technological trajectories - A suggested interpretation of the determinants and directions of technological change. Research Policy 11, 147-162.

EC-JRC (European Commission - Joint Research Center), 2006. Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Well-to-Wheels Report, Version 2b, May 2006. http://ies.jrc.ec.europa.eu/WTW.

EEA (European Environment Agency), 2006. Transport and environment: facing a dilemma. EEA Report 3/2006, www.eea.eu.int.

EPA (Environmental Protection Agency), 2006. Greenhouse Gas Emissions form the U.S. Transportation Sector 1990-2003. www.epa.gov/otaq/climate.htm.

Frenken, K., Nuvolari, A., 2004. The early history of steam engine technology: an evolutionary interpretation using complexity theory. Industrial and Corporate Change, 13 (2), 419-450.

Frenken, K., 2006. Innovation, Evolution and Complexity Theory. Edward Elgar, Cheltenham, UK.

Friedrich, R., Bickel, P. (eds), 2001. Environmental External Costs of Transport. Springer-Verlag Berlin Heidelberg New York.

GM, LBST, BP, ExxonMobil, Shell, TotaFinaElf, 2002. Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study. http://www.lbst.de/.

Hekkert, M.P., Hendriks, F.H.J.F., Faaij, A.P.C., Neelis, M.L., 2005. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. Energy Policy 33, 579-594.

Kauffman, S.A., 1993. The Origins of Order - Self-Organization and Selection in Evolution. Oxford University Press, New York.

Kemp, R., 1994. Technology and the Transition to Environmental Sustainability. Futures 26(10), 1023-1046.

Levinthal, D.A., 1998. The slow pace of rapid technological change: gradualism and punctuation in technological change, Industrial and Corporate Change 7, 217–47.

Lipman, T.E. 2004. What Will Power the Hydrogen Economy? Present and Future Sources of Hydrogen Energy. Institute of Transportation Studies Report UCD-ITS-RR-04-10, UC Davies, CA, http://www.its.ucdavis.edu/publications/2004/UCD-ITS-RR-04-10.pdf

MIRI (Mizuho Information & Research Institute), 2004. Well-to-Wheel Analysis of Greenhouse Gas Emissions of Automotive Fuels in the Japanese Context - Well-to-Tank Report. http://www.mizuho-ir.co.jp/english/.

NRC (National Research Council), 2004. The Hydrogen Economy – Opportunities, Costs, Barriers and R&D Needs. National Academies Press, Washington, DC.

Ogden, J.M., Wiliams, R.H., Larson, E.D., 2004. Societal lifecycle costs of cars with alternative fuels/engines. Energy Policy 32, 7-27.

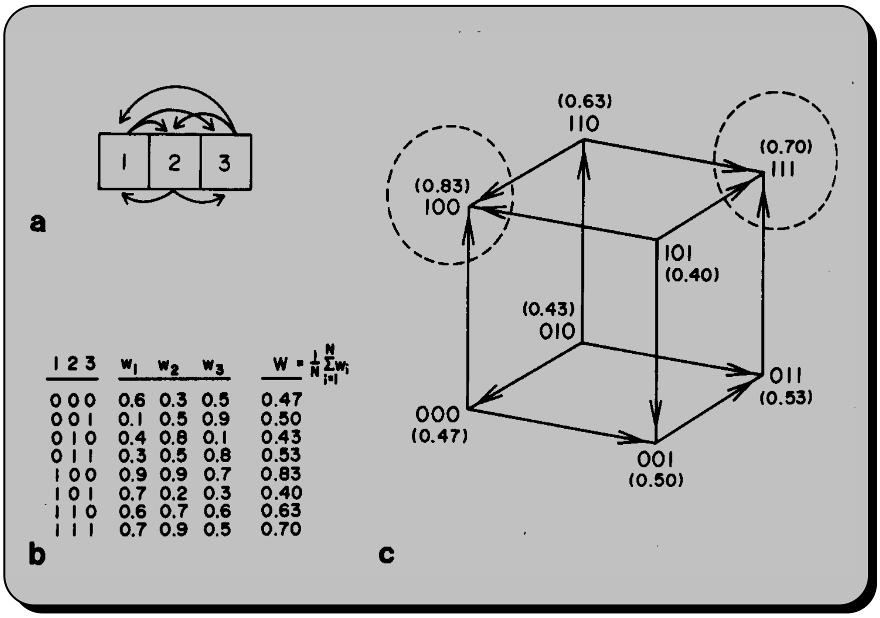
Simon, H.A., 1969. The Sciences of the Artificial, Cambridge MA and London: MIT Press, 3rd edition, 1996.

Tushman, M.L., Anderson, P., 1986. Technological Discontinuities and Organizational Environments. Administrative Science Quarterly 31 (3), 439-465.

Wang M., 2002. Fuel Choices for Fuel-Cell Vehicles: Well-to-Wheels Energy and Emission Impacts. Journal of Power Sources 112, 307-312.

Westheide, E. 1998. Die Einführung bleifreien Benzins und des Katalysators. 15 Jahre Pkw-Abgasgesetzgebung in Deutschland und Europa. Gefahrstoffe, Reinhaltung der Luft 7, 303-306.

Ziman, J., 2000. ed. Technological Innovation as an Evolutionary Process (Cambridge: Cambridge University Press).



1 2 3	w_1	w_2	w_3	$W = \frac{1}{N}\sum_{i=1}^{N} w_i$
0 0 0	0.6	0.3	0.5	0.47
0 0 1	0.1	0.5	0.9	0.50
0 1 0	0.4	0.8	0.1	0.43
0 1 1	0.3	0.5	0.8	0.53
1 0 0	0.9	0.9	0.7	0.83
1 0 1	0.7	0.2	0.3	0.40
1 1 0	0.6	0.7	0.6	0.63
1 1 1	0.7	0.9	0.5	0.70

Figure 1: (a) architecture of a complex system with three subsystems, (b) fitness table, (c) design space and corresponding fitness landscape (from Kauffman, 1993, p. 42). The design space contains eight combinations. Combination 100 is the global optimum and combination 111 is a local optimum.

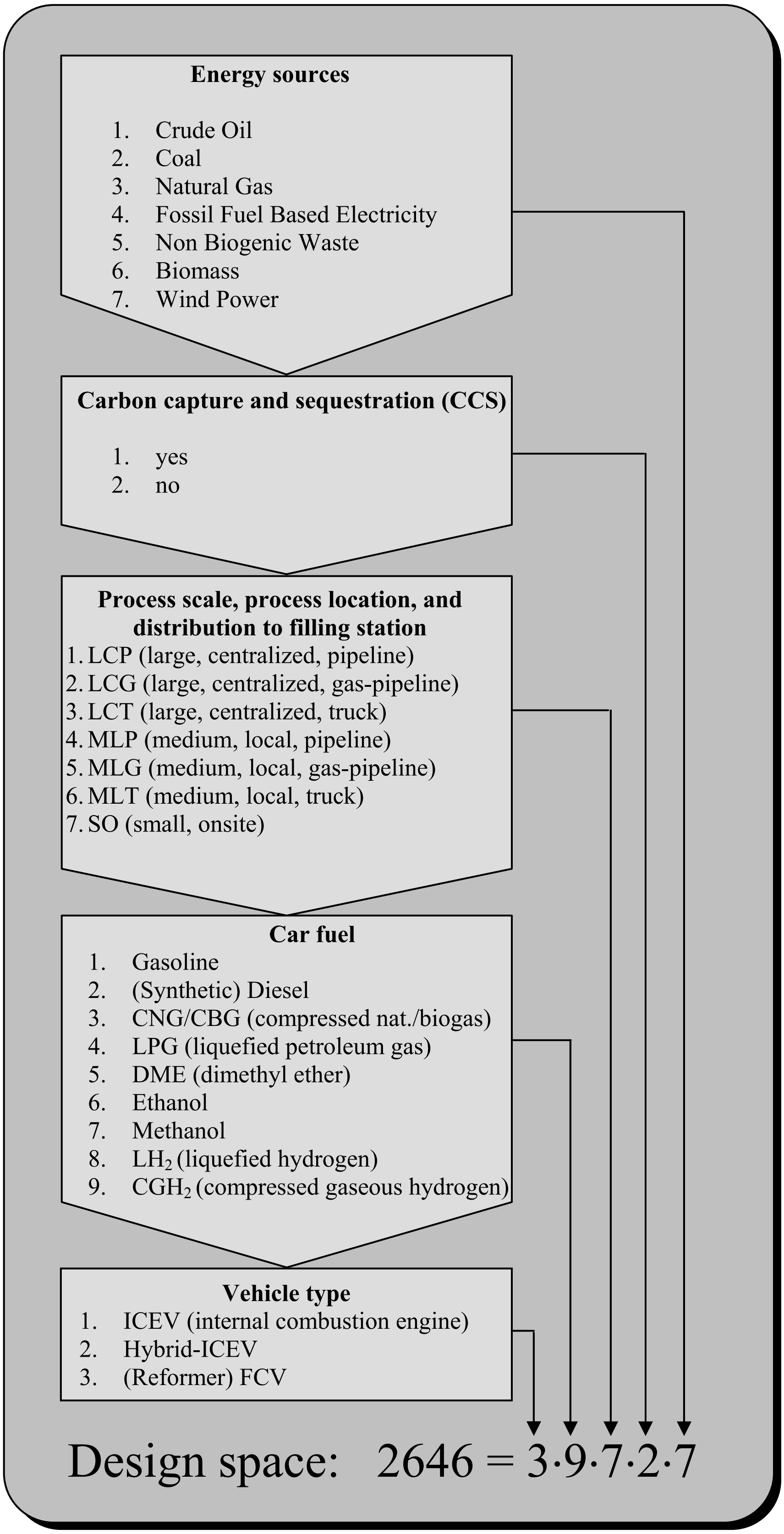


Figure 2: WTW chain decomposed to subsystems

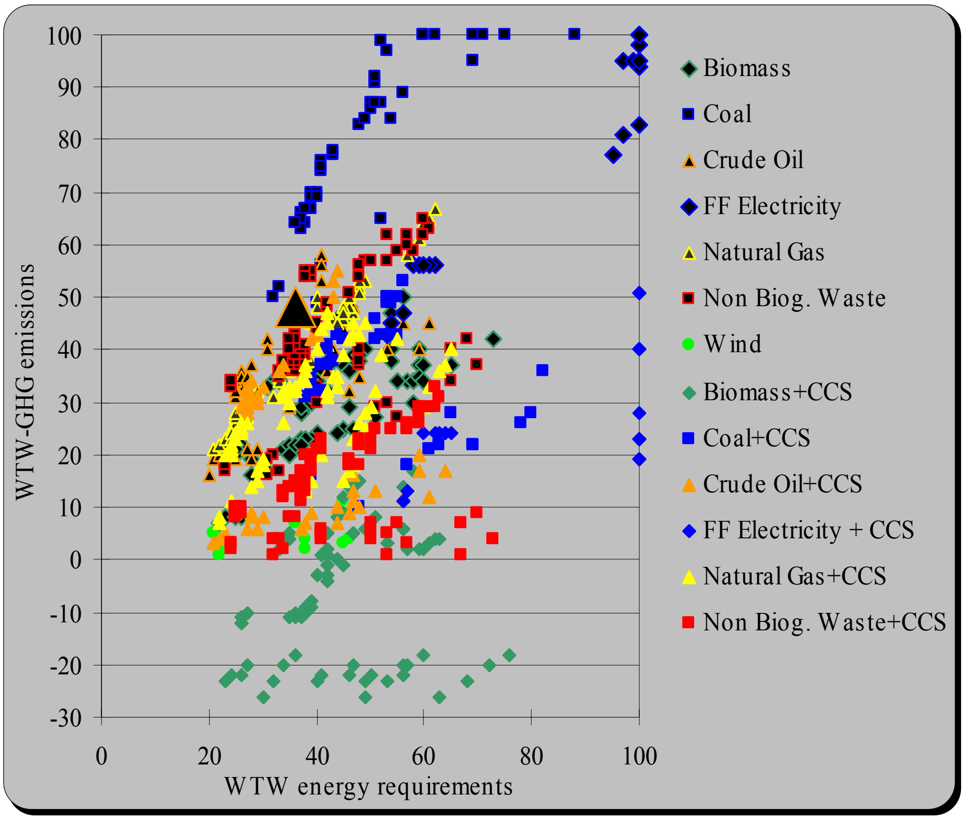


Figure 3: WTW-chain performance grouped by energy sources and CCS applied

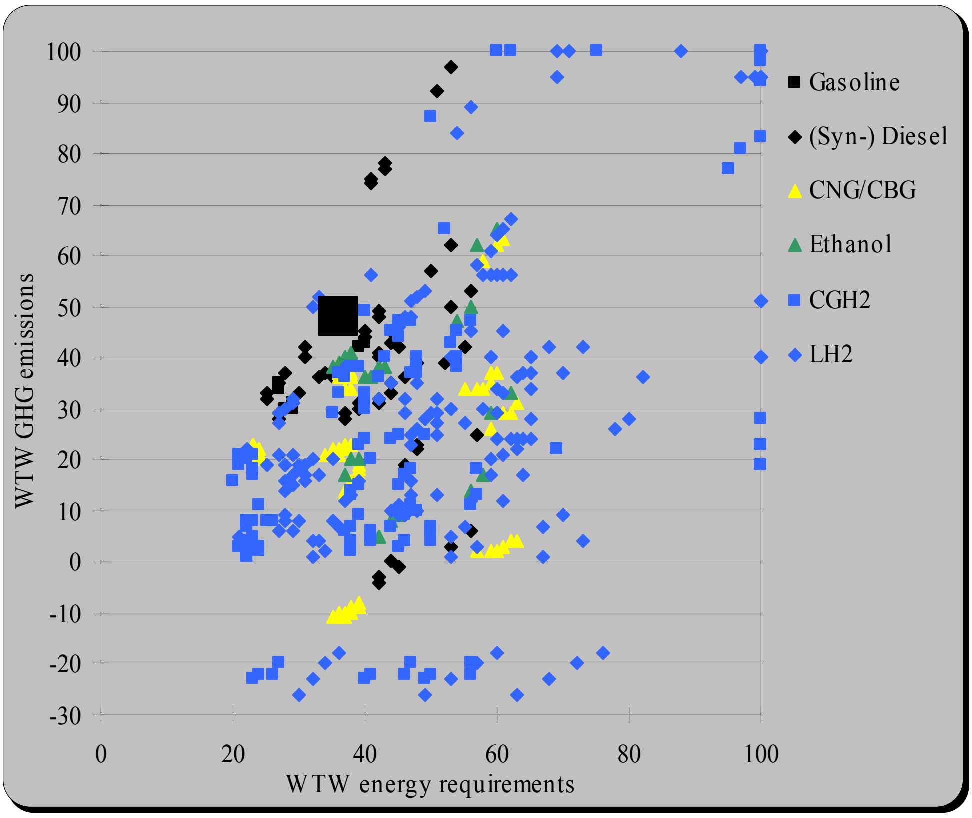
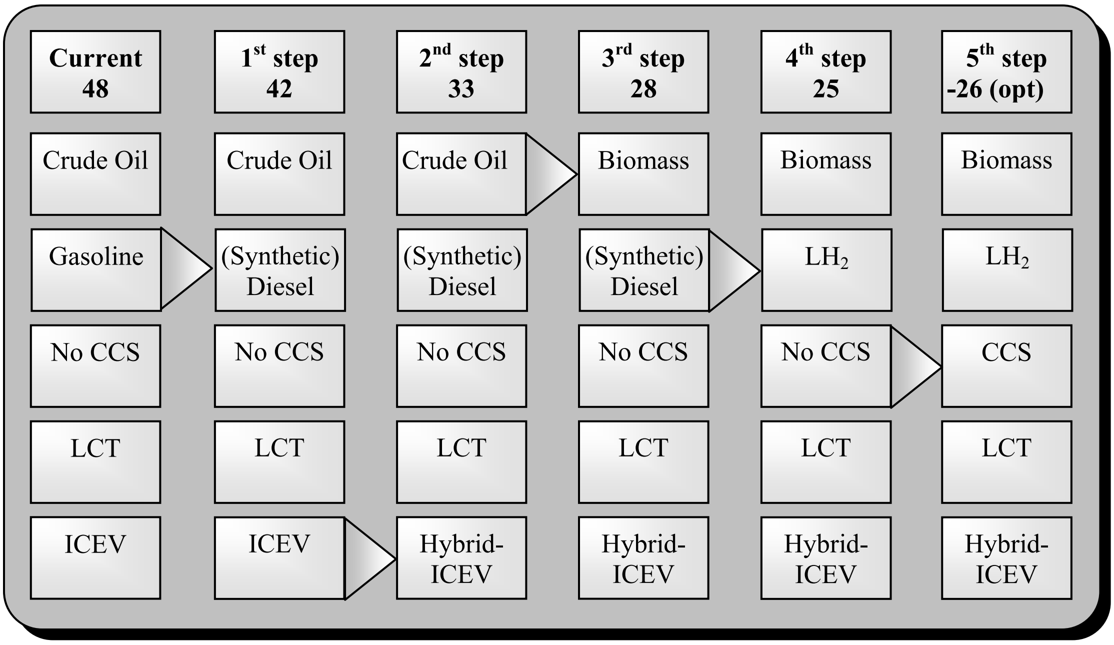
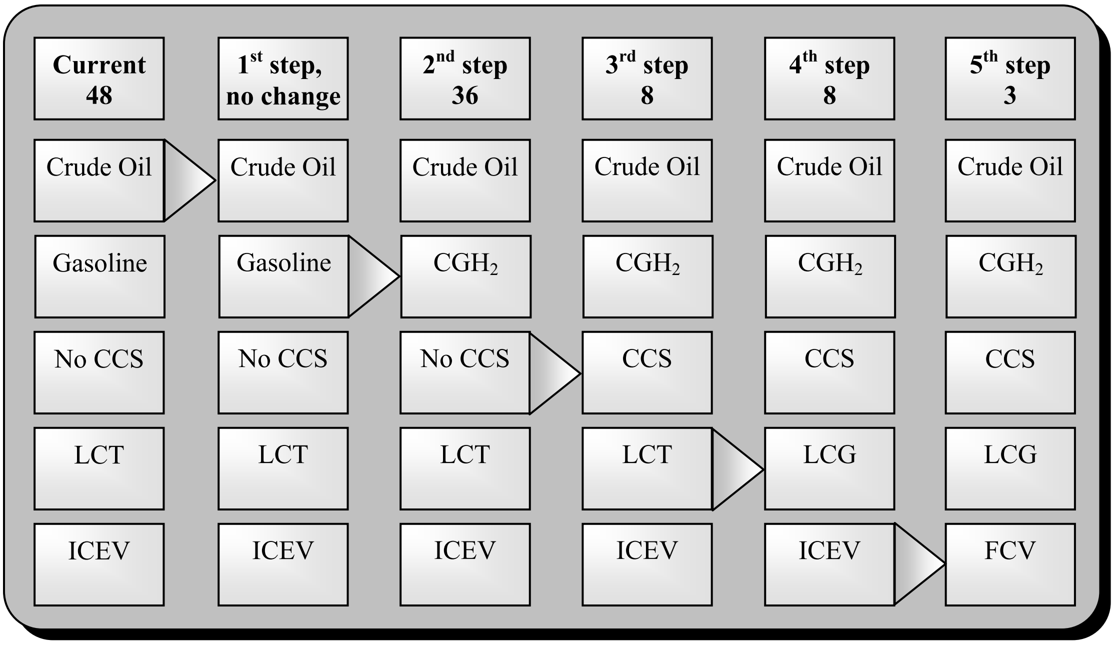


Figure 4: WTW-chain performance grouped by car fuels



Current 48	1st step 42	2nd step 33	3rd step 28	4th step 25	5th step -26 (opt)
Crude Oil	Crude Oil	Crude Oil	Biomass	Biomass	Biomass
Gasoline	(Synthetic) Diesel	(Synthetic) Diesel	(Synthetic) Diesel	LH_2	LH_2
No CCS	No CCS	No CCS	No CCS	No CCS	CCS
LCT	LCT	LCT	LCT	LCT	LCT
ICEV	ICEV	Hybrid-ICEV	Hybrid-ICEV	Hybrid-ICEV	Hybrid-ICEV

Figure 5: Example for an emission reducing transition to the GHG emission optimum



Current 48	**1st step, no change**	**2nd step 36**	**3rd step 8**	**4th step 8**	**5th step 3**
Crude Oil	Crude Oil	Crude Oil	Crude Oil	Crude Oil	Crude Oil
Gasoline	Gasoline	CGH_2	CGH_2	CGH_2	CGH_2
No CCS	No CCS	No CCS	CCS	CCS	CCS
LCT	LCT	LCT	LCT	LCG	LCG
ICEV	ICEV	ICEV	ICEV	ICEV	FCV

Figure 6: Example for an emission reducing transition following a myopic decision rule

Table 1: Optima of WTW performance measures

	WTW energy requirements			**WTW GHG emissions**
	20 (Global optimum)	**21 (Local optimum *A*)**	**22 (Local optimum *B*)**	**-26 (Global optimum)**
Energy sources	Crude Oil	Wind Power	NG	Biomass
CCS	no	(no)	no	yes
Process scale, process location, and distribution	LCG LCT	MLT	LCG LCT MLG MLT SO	LCT
Car fuel	CGH2	LH$_2$	CNG	LH$_2$
Vehicle type	FCV	FCV	Hybrid-ICEV	ICEV Hybrid-ICEV FCV

Table 2 Optima of WTW performance measures with higher uncertainty (interval length 5)

	WTW energy requirements									WTW GHG emissions	
	20 (Global optimum *A*)								20 (Global optimum *B*)	-25 (Global optimum)	
Energy sources	Biomass	Crude Oil	Crude Oil	Crude Oil	NG	NG	Wind Power	Wind Power	NG	Biomass	Biomass
CCS	no	no	yes	no	yes	no	(no)	(no)	no	yes	yes
Process scale, process location, and distribution	LCT	LCG LCT MLT SO	LCG LCT MLT	SO	LCG LCT MLG MLT	LCG LCT MLG MLT	MLG MLT SO	MLG MLT SO	LCP LCT MLG MLT SO	LCG LCT	LCG LCT
Car fuel	CGH_2	CGH_2	CGH_2	LH_2	CGH_2	CGH_2	CGH_2	LH_2	CNG	LH_2	CGH_2
Vehicle type	FCV	FCV	FCV	FCV	FCV	FCV	FCV	FCV	Hybrid-ICEV	ICEV Hybrid-ICEV FCV	ICEV Hybrid-ICEV FCV

Table 3: Shortest transition path (average performance along the path in brackets)

	WTW energy requirements			WTW GHG emissions
First transition step:	**Global optimum**	**Local optimum (*A*)**	**Local optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	-	3 (9.3)
Transition to LCP	4 (27.5)	5 (27.6)	6 (26.2)	5 (23.6)
Transition to Diesel	3 (26.3)	5 (26.8)	5 (25.4)	4 (13.8)
Transition to LH_2	-	-	-	4 (-1.5)
Transition to CGH_2	-	-	-	3 (8.7)
Transition to Hybrid-ICEV	3 (24.7)	5 (25.8)	4 (24.5)	4 (12.0)
Transition to FCV (+reformer)	2 (23.5)	4 (25.5)	5 (24.2)	4 (8.3)

Table 4: Number of transition paths to the optima within 5 transition steps

	WTW energy requirements			WTW GHG emissions
First transition step:	**Global optimum**	**Local optimum (*A*)**	**Local optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	-	50
Transition to LCP	11	1	0	1
Transition to Diesel	14	1	2	59
Transition to LH_2	-	-	-	47
Transition to CGH_2	-	-	-	11
Transition to Hybrid-ICEV	15	2	7	32
Transition to FCV (+reformer)	27	5	4	22

Table 5: Shortest transition path (average performance along the path in brackets, high uncertainty)

	WTW energy requirements		WTW GHG emissions
First transition step:	**Global optimum (*A*)**	**Global optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	3 (6.7)
Transition to LCP	4 (26.3)	6 (25.8)	5 (22.0)
Transition to MLP	4 (26.3)	6 (25.8)	5 (23.0)
Transition to MLT	3 (26.7)	5 (26.0)	5 (11.0)
Transition to Diesel	3 (26.7)	5 (25.0)	4 (13.8)
Transition to LPG	-	-	4 (15.0)
Transition to LH_2	-	-	3 (8.3)
Transition to CGH_2	-	-	3 (5.0)
Transition to Hybrid-ICEV	3 (23.3)	4 (23.8)	4 (11.3)
Transition to FCV (+reformer)	2 (22.5)	5 (24.0)	4 (7.5)

Table 6: Number of transition paths to the optima within 5 transition steps (high uncertainty)

	WTW energy requirements		**WTW GHG emissions**
First transition step:	**Global optimum (*A*)**	**Global optimum (*B*)**	**Global optimum**
Transition to CCS	-	-	106
Transition to LCP	36	0	2
Transition to MLP	36	0	2
Transition to MLT	49	1	26
Transition to Diesel	51	1	134
Transition to LPG	-	-	156
Transition to LH_2	-	-	134
Transition to CGH_2	-	-	77
Transition to Hybrid-ICEV	53	8	79
Transition to FCV (+reformer)	97	5	68

Table 7: Number of win-win transition paths to the optima within 5 transition steps

	WTW energy requirements		
First transition step:	**Global optimum**	**Local optimum (*A*)**	**Local optimum (*B*)**
Transition to Diesel	9	2	-
Transition to Hybrid-ICEV	-	-	2
Transition to FCV (+reformer)	5	-	2

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Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55** (forthcoming, *Climatic Change*)

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Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), *Climate change and international tourism: a simulation study,* **FNU-31** (*Global Environmental Change,* **15** (3), 253-266)

Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, **FNU-30** (*ICES Journal of Marine Science*, **63** (4), 611-625)

Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, **FNU-29** (*Essener Geographische Arbeiten*, **35**, 179-202)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, **FNU-28** (*Ocean & Coastal Management*, No. 48 (2005), pp. 115-159.)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27** (*China Environment Series,* Issue 6, pp. 120-124; http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf)

Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26** (*Integrated Assessment,* **6** (1), 75-82)

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Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).

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Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of* FUND, **FNU-16** (forthcoming, *Climatic Change*).

Hamilton, J.M. (2003), *Climate and the Destination Choice of German Tourists,* **FNU-15** (revised and submitted).

Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of* FUND, **FNU-14** (*Climate Policy,* **4**, 269-287).

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (forthcoming, *Climatic Change*).

Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of* FUND, **FNU-12** (forthcoming, *Environment and Development Economics*).

Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (*Ecological Economics*, **54**, 397-416).

Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (*Resource and Energy Economics*, **27**, 1-17).

Tol, R.S.J.and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (*Energy Policy*, **32** (9), 1109-1130).

Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (*Environmental and Resource Economics*, **28**, 209-232).

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted).

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l'Air Propre?*, 155-179).

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics,* **1** (4), 179-206)

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).