

Chapter 5

The Role of Social Norms for the Diffusion of Eco-Innovations: Tipping Point, and Lock-in Effects

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Abstract In the innovation literature, paradigm changes in supply have been elaborated during the last three decades, while interdependencies between technology competition and social norm changes on the demand-side have received less attention. This paper investigates the concept of the social norm to model green product diffusion. It offers a social perspective on the systemic phenomena of tipping point and lock-in effects in relation to green product diffusion; this is our first contribution. Social interaction effects of distinct technology adoption patterns are conceptualized as social norm competition. We apply the method of simulation based theory building, to test the system behavioral implications of the postulated nonlinear socio-technical norm effect. We show that this conception provides an endogenous explanation of tipping behavior in s-shaped diffusion models. This complements pure probabilistic technology diffusion models that neglect both endogenous and social influences on adoption decisions. We perform simulations for two and three competing technologies, using the example of vehicle fleet penetration with alternative drivetrain technologies. We show that the critical mass and the transition pathway is path dependent. Our second contribution is the specification of the critical mass within distinct socio-technical norm regimes. We apply a mathematical analysis of the technological landscape potential to visualize the characteristics of the tipping point. The tipping point is explained by the built up of a critical mass of users that signal a new socio-technical norm fostering transition to irreversible substitution. The offered approach and perspective is intended to be useful for effective long term policy making and to enhance the intuition about feedback rich sustainability transitions.

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5.1 Introduction

Understanding processes that link societal needs, and institutional changes (e.g. social norm building) with green product diffusion becomes increasingly important for mastering socio-technical sustainability transitions (Geels and Schot 2007). The innovation literature reflects a long history of innovation diffusion research and modeling. The pioneering work on diffusion of innovations is credited to Rogers (1962) and Bass (1969). Their models mapped positive effects of advertising and imitation. Robinson and Lakhani (1975) introduced negative influence on adoption within their model. Subsequent work by Christensen (1997) and Rogers (2003) directed attention towards the notion of tipping points in the diffusion process. The notion of a tipping point refers to critical mass, bifurcation, or threshold values in a nonlinear system and is related to systemic phenomena such as lock-in and path-dependencies. These phenomena have attracted the interest of social scientists in multiple fields including economics (David 1986; Arthur 1989; Arrow 2000; Unruh 2000; Arrow 2004; Stonemann 2004), politics (Pierson 2004), managerial and organizational schools of thought (Sydow et al. 2009; Thrane et al. 2010) and sustainability science (Rotmans et al. 2001; Geels 2004; Geels and Schot 2007). They refer to models, which explain lock-in and break-out effects as interactions between sub-system and different selection environments. However, they explain the causes of a bifurcation or of a tipping point in product markets at rather abstract levels. In addition the definition of a tipping point has not been formalized, and therefore remains a vague concept (Phillips 2007). Phillips' analysis of different probabilistic models (2007) has begun to shape the mathematical

characterization of a tipping point. He compared 1-, 2- and 3-parameter probabilistic models and showed that a 3-parameter formulation is needed to describe a tipping point exogenously, as it is understood in today's managerial science: a transition to irreversible growth. But, this analytical understanding does not yet explain what real world counterpart creates the resistance that must be incorporated into the model, as demanded by Philipps (2007) and still provides 'a snap shot' understanding of an intrinsic dynamic process. Positive feedback that creates increasing returns may be one important economic dynamic aspect. Diffusion theory (Rogers 2003) and social psychology (Ajzen and Fishbein 1970; Schelling 1971; Latané 1981; Schwartz and Howard 1981; Rohlfs 2003) for example give evidence that more careful attention to the social context should be paid to understand the determinants, mechanisms of adoption or not-adoption. However, social norms often have been considered as stable parameters in path dependency analysis and product diffusion models. While these assumptions may be valid in economies with stable environments, they are limited in economies with changing environments. Today, increasing energy security threats and climate change are such global changes that affect whole societies. Such societal threads induce paradigm changes in industries, and norm or preference changes in markets fostering eco-innovations and diffusion. Therefore, understanding processes that link green product diffusion with social norm research becomes increasingly important. However, it is difficult because the different research fields often refer to different situations, and apply different perspectives and methods. In this paper we address this challenge. Our first contribution is to clarify the link between green product diffusion and social norm effects. We offer an *endogenous perspective* on socio-technical norm effects and link them to the systemic phenomena of tipping point and lock-in effects. We analyze the effect of social norm changes in a market with multiple competing technologies. How should the tipping point be explained? How should it be specified? What is the effect of multiple competing eco-technologies on path dependency and diffusion pathways? By answering these questions, we aim to establish a dynamical understanding of the concept of critical mass; this is our second contribution. Therefore, we apply simulation based theory building (Davis et al. 2007). For illustrative purpose we present the case of green passenger car diffusion with different drive train technologies.

The paper has been organized as follows. The first section has provided the general overview and the objectives of the study (Sect. 5.1). Section 5.2 provides the theoretical background on the main concepts. These include social norm in adoption decisions, and the systemic phenomena critical mass, tipping point, lock-in and path dependency. An explanation frame based on social norm dynamics is introduced. Sect. 5.3 summarizes the simulation model that is based on the explanation frame introduced in the previous section. Section 5.4 provides a mathematical analysis of the model in order to provide an intuitive understanding of the critical mass and the acting driving forces in the model. Section 5.5 discusses the insights and provides a systematic and more abstract picture on socio-technical norm regimes, tipping points and the critical mass in a force field. Section 5.6 summarizes our findings and assesses the implication of the study for policymaking and further research. Limitations are pointed out.

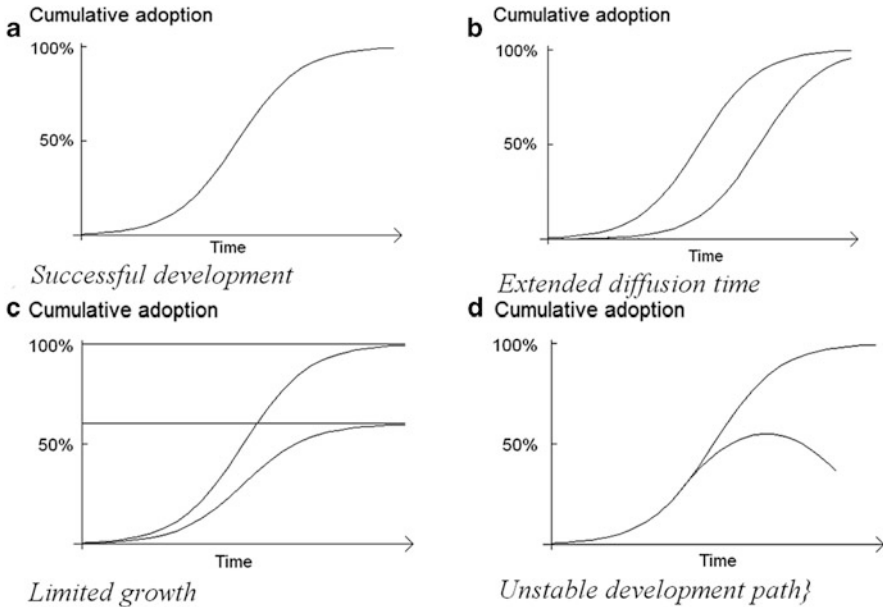


Fig. 5.1 Fundamental qualitative behavior patterns of s-shaped growth. Complete adoption goes from 0 % to 100 %, time in arbitrary units

5.2 Tipping Points and Social Norm Effects in Green Product Diffusion

5.2.1 Innovation Diffusion Pathways

Most diffusion models are able to reproduce s-shaped diffusion patterns as described by the theory of Rogers, but the concepts critical mass and tipping point are often not addressed or only vaguely circumscribed (Phillips 2007; Ullibeer et al. 2010). Rogers identifies a ‘point of no return’ in a diffusion process. It becomes manifest in the number of adopters of a technology, the critical mass (Rogers 2003) that is needed for the further rate of adoption to become self-sustaining. At this point stimulating measures are no longer needed for the diffusion process to proceed to saturation. Due to different initial conditions and tipping point characteristics of innovation diffusion fundamental qualitative patterns of s-shaped growth or decline can be observed. A simplified, idealized innovation diffusion that follows an s-shaped cumulative adoption curve (Rogers 2003) is shown in Fig. 5.1a. The graph shows the percentage of adoption for one technology (y-axis) plotted against time (x-axis). We refer to a successful development, if the curve follows an s-shaped form that reaches a desired level within an acceptable time frame, i.e. the

level and the timeframe of a reference technology in a reference market. Possible failures would be an extended diffusion time (diffusion takes more time than acceptable, Fig. 5.1b), a limited growth (diffusion does not reach a desired level, Fig. 5.1c) or rejection (start-up of diffusion with subsequent decline, Fig. 5.1d).

An appropriate diffusion model and the explanatory theoretical framework upon which it is built must be able to reproduce and explain the different types of behavior described above. Ulli-Beer et al. (2010) have shown that growth in the Bass model (Bass 1969) is basically self-catalytic, and lacks a tipping point in terms of a transition to irreversibility. A model that does not map acceptance and rejection (behavior patterns shown in Fig. 5.1d) is limited to describe only successful growth. Ulli-Beer et al. (2010) identify the tipping point with the critical mass of adoption that shift the dominance of two competing social norms, and present an exact analysis of acceptance and rejection dynamics. Building on their analysis, we argue that the critical mass in markets should also be theoretically founded in the concept of the social norm. We investigate the case of two and three competing technologies in a substitution process and address the following three *Research Questions*:

1. How should tipping point dynamics in green product diffusion be explained?
2. Under what conditions does one eco-technology become dominant in a substitution process?
3. What is the effect of the number of competitors?

In order to address the first leading research, we give a short summary on the concepts of critical mass and social norms, as well as lock-in and path dependencies, which are traditionally treated in separate bodies of research.

5.2.2 Conceptual Links Between Social Norm Building, Critical Mass and Path Dependency

According to Rogers (2003) *critical mass* is a fundamental concept that expresses the social nature of technology diffusion. Rogers characterizes ‘reaching the critical mass’ as the ‘moment when the adoption rate experiences an acceleration’. The critical mass is described as the cumulative adopter share, which a technology must reach in order to succeed in a market. From a micro-economic perspective, a threshold of utility has to be exceeded for a customer to adopt a certain technology, that depends on the number of previous adopters of a technology (Arthur 1989; Dolfsma and Leydesdorff 2009). On a more aggregate level, it corresponds to a tipping point in technology substitution, after which social pressure becomes strong enough to induce a self-sustaining bandwagon effect (Rohlfes 2003). The social pressure concept can be directly linked to social norms of a group of people (Schwartz and Howard 1981), and to individuals’ personal norms (Ajzen and

Fishbein 1970). Both are decisive concepts for the explanation of human behavior in (social) psychology. The psychological focus theory of normative conduct describes the perception of prevalent behavior as a driving force of individual behavior and is commonly referred to as the descriptive (social) norm (Cialdini et al. 1991). Such social norms are seen as social behavior rules telling a group of people, how they should behave in a given situation. In socially complex behavior contexts they have an important coordination function. They are internalized and lead to un-reflected behavior patterns that are hard to change (Cialdini and Trost 1998; Kahan 2000). Establishing a new norm (for example, to mitigate a collective action problem such as global warming) is therefore often costly for individuals due to the old norm itself, which stigmatizes any deviation from it (Akerlof 1980; Kübler 2001). Although the empirical evidence of the relation between social norm and consumer acting has been established in the literature (Latané 1981; Cialdini and Trost 1998; Vatter et al. 2001; Ulli-Beer 2006), Nolan et al. (2008) showed that “descriptive norms” have a powerful but under-detected effect on the important social behavior of “energy conservation”.

According to Fisher and Pry (1971), advancing technology allows the user to perform an existing function or satisfy a need in a different way. Fisher argues that change is rarely radical, and once competitive substitution has progressed to a few percent, it would proceed towards completion. This assumption seems to be overly optimistic for eco-innovations. Disconfirming examples may be found regarding penetration of the passenger car fleet by cleaner drivetrain vehicles. In New Zealand (Janssen 2004) and the Netherlands (Liu et al. 1997), the fleet penetration reached 10 % for natural gas vehicles in the mid-1980s and 8.6 % for liquefied petroleum gas vehicles in 1995. Both fleet shares decreased again, showing that this assumption does not hold in general.

Economic application and operationalization provide the most developed discussion of lock-in and breakout of a path-dependency. Positive feedback is the crucial feature of a historical process that generates path-dependence (Arthur 1994; David 2001). David (2001) provides a broad definition of a path dependent stochastic process. It “is one whose asymptotic distribution evolves as a consequence (function of) the process’s own history” (19). That means that a historical event or strategic decision can lead to irreversible branching processes of product diffusion and the development of industries or markets. In economics, positive feedback processes are operationalized by increasing returns that may be the result of large set-up costs, learning effects, coordination effects, and adaptive expectations (Arthur 1994). Building on this line of research, Dolfsma and Leydesdorff (2009) show how lock-in results from two selection environments that involve positive feedback processes, and how break-out from a lock-in can be generated if a third selection environment with a further positive feedback begins to interact with the two locked-in ones. These models explain lock-in and breakout effects as interactions between sub-systems and different selection environments, but only vaguely address the causes of a bifurcation or of a tipping point in product markets.

5.2.3 *The Dynamics of Green Product Diffusion: Linking Technology Competition and Social Norm Building*

Based on these grounds, we suggest that the concept of social norm needs to be considered as an important determinant of diffusion patterns of eco-innovations in markets. The primary advantage of eco-innovations is their superior ecological performance compared to relevant alternatives. Hence eco-innovations help to reduce the risk of harmful or undesired environmental change, which is a societal value, but only an indirect value added for the users. Therefore, eco-innovation adoption is based on values and beliefs concerning what are the right things to choose rather than mere private utility calculations. Particularly, the choice of eco-innovations becomes a function of the perceived prevalent choice of relevant adopters (Schwartz and Howard 1981). Therefore social norms also stabilize behavior patterns in complex decision situations (including the choice between different competing drivetrain technologies that provide uncertain direct and indirect transport utility). The perception of prevalence is often nonlinearly correlated with the number of adopters; only a recognizable new minority may induce a shift in the social norm that leads to a tipping point in the diffusion process (Schelling 1971). Consequently, social norm building processes may also lead to a lock-in in the dominant technological design, similar to processes as described by Arthur (1989). An example for a demand lock-in would be the case in the passenger vehicle market. In the past, the US and European automobile industries have pursued a development strategy with a low *emphasis on reduced fuel consumption*, increasing power and weight of new vehicles, triggered by the prevalent consumer demand (Bandivadekar et al. 2008). This led to the technological paradigm of typically high-powered, large vehicles supplied by the industry, and established a strong social norm based on the high number of adopters. This social norm influenced the purchase decision of potential buyers towards the same type of vehicle increasing consumer demand. This type of behavior illustrates how a dominant technological design is stabilized by social norm dynamics in the market. However, today we can observe a shift towards a stronger *emphasis on reduced fuel consumption* (Ulli-Beer et al. 2011); this may be attributed to technology paradigm change (Dosi 1982), or a double loop learning process in organizations (Argyris and Schoen 1996; Dosi et al. 1999), or to social norm changes in the market, as discussed in this paper. Probably, it may be best described as a co-evolutionary process involving different rule shifts in the linked subsystems.

The examples give evidence that a discontinuous change may be necessary for inducing a self-sustaining diffusion path that is not only based on a critical share of adopters but also on the strength of the social norm. In order to erode the social norm of the prevalent petrol and diesel vehicles, a respected group of opinion leaders needs to attach a new social value to a unique feature of the new technology, for example, the high eco-friendliness. They need to establish the recognizable new minority (Schelling 1971). The motivation for innovators and early adopters to adopt a eco-innovations may be to mitigate the collective action problem of climate

change (Kübler 2001). These are often a niche population of users that have developed more distinct product preferences than the mainstream (Levinthal 1998). In other words, eco-innovation uptakes may result when opinion leaders realize a need and opportunity for alternative actions. Ulli-Beer et al. (2010) have developed a double-loop acceptance framework that explains how social norm dynamics are overriding utility evaluations (see also Kopainsky et al. 2012). The social norm is initiated by new distinct behavior patterns of a recognizable new minority of early adopters that respond to undesired long-term consequences of the dominant technology design. Eventually, these early adopters may provide a new social norm to successive adopters that cumulate in the stock of the recognizable new minority increasing the strength of their social norm.

While innovators launch the new technology, deliberate adoption decisions of opinion leaders trigger a new social norm within a social-technical system. That is the reason why innovators and opinion leaders are critical to solve the start-up problem of a new technology. Succeeding adopters reinforce the prevalence of the new purchase pattern, and subsequently the social norm effect on the adoption decision. These social interaction effects of distinct purchase patterns can be understood as social norm competition. As soon as the new social norm dominates and guides an increasing number of adoption decisions, the diffusion process reaches the critical mass of adopters and crosses the tipping point, where the process becomes self-sustaining. With this description, we complement Roger's statistically derived adopter categories by an explanation framework based on *social norm dynamics*. It offers a better understanding on how self-enforcing social norm building and the concept of eco-innovativeness may be used to explain and simulate the diffusion of green products, in general, and the related tipping point or lock-in phenomena, in particular.

To conclude our theoretical discussion, we argue that in the context of green product diffusion, the critical mass should be anchored in the concept of *nonlinear social norm dynamics*, because societal issues are the main triggers of eco-innovations and their wide spread use. In the following, we will illustrate the macro effects of social norm dynamics, creating tipping behavior and path dependency. For this purpose, we introduce a system dynamics model for the case of eco-innovations in the passenger car fleet.

5.3 The System Dynamics Model for the Market Penetration of Alternative Drivetrain Technologies

We have developed a SD model to endogenously simulate the market penetration of alternative drivetrain technologies (Bosshardt 2009; Ulli-Beer et al. 2011). It is based on the above introduced explanation frame of social norm dynamics in green product diffusion. In this paper, we describe the simplified structure that

operationalizes the structure of social norm dynamics and allows analyzing the behavioral impact on the diffusion path. We aim at increasing the understanding about the potential effect of social norm dynamics on the emergence of a tipping point, and the required critical mass considering an increasing variety of technology options. Therefore, the model is applied to two and later three competing drivetrain technologies in the passenger car market. Our focus is on the adopter potential, a variable describing the consumer choice, moderating the sales rates of the vehicle technologies and thus the substitution rate. The adopter potential depends on three arguments for the consumers' purchase decision:

Comparative attractiveness summarizes the factors influencing the monetary utility of a drivetrain technology, such as purchase and fuel prices, as well as the drivers' satisfaction of infrastructure needs and vehicle type spectrum. The approach of discrete choice modeling with logit functions can be applied to calculate the probability of purchase when accounting for cost criteria.

Social norm is the internal social pressure. The force is positively related with the technology-specific adopter potential and rate of adoption. Its value is given by a nonlinear, s-shaped function of the number of the technology-specific installed vehicle stock (Schelling 1971; Ulli-Beer 2006). It operationalizes the cumulative, normative influence of the increasing prevalence of a new vehicle technology. The normative social influence is the impulse to imitate observed behavior. Observed behavior, in this sense, refers to the recognizable new minority who has already adopted the new vehicle technology.

Inherent attractiveness comprises technological attributes, which are not covered by monetary, infrastructural or normative social considerations. It represents the evaluation of a technology due to its attributed potential to address new or existing needs, values and beliefs of potential adopters and the broader society. In terms of Rogers' categories of 'perceived attributes of innovation', it fits best with the compatibility concept. However, the notion *inherent attractiveness* also captures the aspect of a promise and potential a technology portends. It is an attributed compatibility with a newly debated norm for solving a collective action problem. Compared to the social norm, the inherent attractiveness is the impulse on innovation that a new drivetrain technology gives. The corresponding technological attributes also trigger the motivation of innovators and early adopters. The inherent attractiveness input data is used as an exogenous parameter in order to analyze the impact of a parameter value change on the overall model behavior as illustrated in Figs. 5.4 and 5.5.

Each drivetrain technology is represented by its vehicle stock. Discards gradually decrease the vehicle stocks, depending on the lifetime of a vehicle. When a vehicle is replaced by a new one, the total of all vehicles is not affected. Fleet growth or decrease is a result of positive or negative new sales, not replacements. Technology substitution means that a discarded vehicle of technology A is replaced by a vehicle of technology B, depending on the drivetrain technologies' attributes. Then the technology specific vehicle stock changes, while the overall fleet stock remains constant. The attributes comparative and inherent attractiveness, as well as

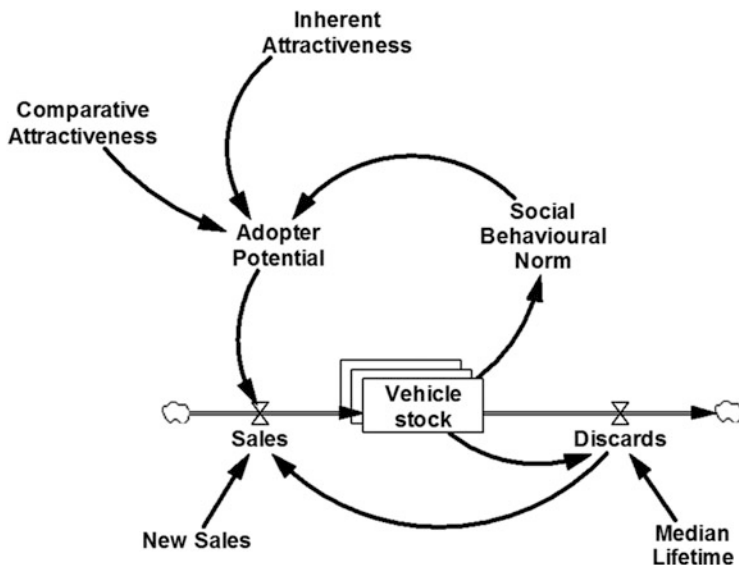


Fig. 5.2 Main structure of the model as applied to multiple technologies (i.e., different vehicle stocks)

the social behavioral norm control the technology-specific adopter potential, a percentage which is assigned to each technology in terms of a market share. The translation into sales rates is achieved by multiplication of the adopter potential with vehicle sales, including both replacement sales and new sales. The structure displayed in Fig. 5.2 shows the interrelationship between the model variables for each technology. It further indicates that this structure is applied to all technology specific vehicle stocks. The adopter potential combines these sub-model structures. The attractiveness and norm values are normalized and used to allocate the market shares to each drivetrain technology. The heart of the model and the most important aspect for the analysis in this paper is the feedback loop featuring the social norm building process. Each drivetrain technology produces a social norm by the presence of its vehicles. This influences the adopter potential (i.e., the consumer’s purchase decision), and via sales affects the vehicle stocks again. In our further analysis we will give evidence that this reinforcing feedback loop of the *socio-technical norm effect* has severe consequences on green product diffusion pathways, i.e. the emergence of path dependencies and tipping points, as well as the identification of a critical mass.

For illustrative reasons the mathematical formulation of the model variable “Sales” will be introduced (see also [Appendix](#). It is the rate equation of the technology specific vehicle stock X_i .

$$\frac{dX_i}{dt} = S_i - D. \quad (5.1)$$

The sales of technology i (S_i) can be expressed by the adopter potential (relative market share) AP_i multiplied with the total sales. The total sales, however, are given by the discards of every drivetrain technology D_k as required by technology substitution, plus new sales (NS):

$$S_i = AP_i \left(\sum_k D_k + NS \right)$$

The discards are obtained by dividing the vehicle stock by the vehicle median lifetime τ .

$$S_i = AP_i \left(\sum_k \frac{X_k}{\tau_k} + NS \right)$$

The adopter potential of drivetrain technology i (AP_i) represents the probability that a consumer buys a vehicle of this platform. It is obtained by normalization of the total perceived attractiveness PA_i over all technologies, that is

$$AP_i = \frac{PA_i}{\sum_k PA_k}$$

where PA_i combines the three consumer choice attributes: behavioral norm SN_i , inherent attractiveness IA_i and comparative attractiveness CA_i . In our model it is given as (Bosshardt 2009)

$$PA_i = CA_i * (SN_i + IA_i - SN_i IA_i)$$

Substitution of the above into Eq. 5.1 yields

$$\frac{dX_i}{dt} = \frac{CA_i * (SN_i + IA_i - SN_i IA_i)}{\sum_k CA_k * (SN_k + IA_k - SN_k IA_k)} \left(\sum_j \frac{X_j}{\tau_j} + NS \right) - \frac{X_i}{\tau_i}. \quad (5.2)$$

We have operationalized and quantified the socio-technical norm effect as a lookup function (cf. Fig. 5.3), using the number of vehicles for each drivetrain technology as input. This input value is normalized to the total of vehicles in the fleet to map perception, or people's everyday life experience. The lookup function outputs a fraction of people willing to adopt the corresponding technology by social pressure.

A fleet share of 0 % will certainly not produce any adopter paradigm. The other extreme case is a complete fleet penetration, where the socio-technical norm effect is limited. We assume that about 5 % of potential adopters do not follow the norm

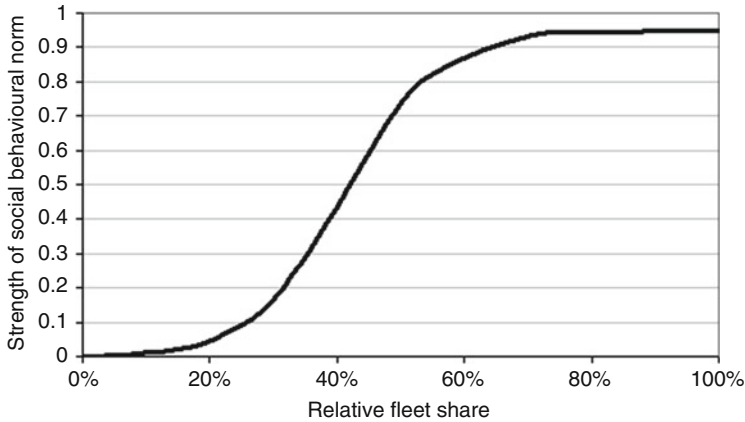


Fig. 5.3 The socio-technical norm effect corresponds with people’s perception of the diffusion of a drivetrain technology in the vehicle fleet. It is modeled by an s-shaped lookup function. Saturation reaches 0.95 for a 100 % fleet share

and must be convinced to adopt by one of the other two factors, inherent or comparative attractiveness. This fraction corresponds to people such as innovators, who adopt new technologies without considering trends, but rather setting trends and enabling diffusion or substitution processes to start (Rogers 2003).

5.4 Model Behavior

We now investigate the behavior of this model with two and three competing technologies. The model is applied to the passenger car market, starting with the competition of internal combustion engine vehicles (ICEs) operated on petrol and diesel. In a second step, an eco-technology, natural gas vehicles (NGVs), is introduced into the market to compete with the conventional ICEs.

5.4.1 Two Competing Technologies

The following model output presented in Fig. 5.4 is based on a scenario for Germany, focusing on competing petrol and diesel ICEs. The observed dominance of petrol ICEs is attacked by an upcoming diesel fraction. The graphs below show the model results for two scenarios, (a) *Persistent ICE Petrol Dominance* and (b) *Establishing ICE Diesel Dominance*. The difference between the two scenarios (a) and (b) is the duration of an increase of the parameter inherent attractiveness of the diesel vehicles as displayed by (i) the inherent attractiveness settings.

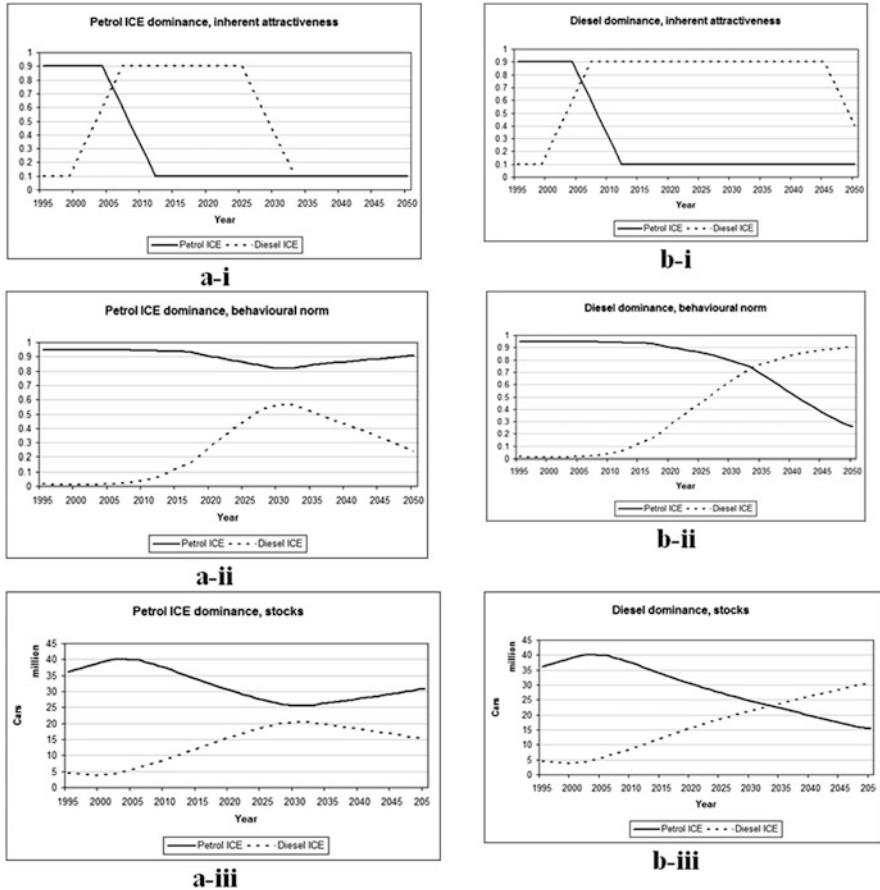


Fig. 5.4 Effect of the established socio-technical norm on the vehicle stocks of competing petrol and diesel ICEs, based on different inherent attractiveness scenarios

The comparative attractiveness is assumed to be similar for both technologies and is kept constant. The consequences for the social behavioral norm (ii) and the corresponding impact on the vehicle stock development (iii) are displayed in the subsequent graphs.

The simulation results highlight typical behavioral characteristics. First, the fleet behavior strongly depends on the development of the social behavioral norm, which is in line with Bass' diffusion by imitation. The strong represented petrol ICE fleet is supported by its highly influential socio-technical norm. Diesels do not have a high installed base, and consequently an ineffective socio-technical norm loop; therefore they need a change in their inherent attractiveness to enlarge their fleet share. Although the inherent attractiveness of petrol vehicles drops, while the inherent attractiveness of the diesels increases (e.g. due to an improved end-of-pipe technology), they remain the dominant drivetrain technology. Second, if the

inherent attractiveness of the diesels ceases before its norm effect has exceeded the norm effect of petrol vehicles, the original states are re-established, as shown in scenario (a). In scenario (b), the inherent attractiveness remains longer on the high level, long enough to build up a dominating social behavioral norm. And finally, even though the inherent attractiveness ceases, the norm loop is strong enough to keep its dominating influence; this is a counterintuitive result according Bass' diffusion by imitation.

However, it establishes evidence that the socio-technical norm loop and its nonlinearity explain tipping point behavior in green product diffusion: the strength of the socio-technical norm effect as a function of the fleet share of diesel ICEs has exceeded a critical *relative* threshold value. Beyond that point, the technology diffusion is successful and stable. According this understanding the *critical mass* can be identified as the required *relative* fleet share that generates a shift in the dominance of competing socio-technical norm processes. The example describes typical behavior patterns of the *class of* green product diffusion challenges involving technology substitution.

5.4.2 Three Competing Technologies

We now describe the socio-technical norm effect on the critical mass that occurs in our model, as soon as at least three drivetrain technologies compete. We apply the model to the same settings as in the case for two competing technologies and introduce a third technology, natural gas vehicles (NGVs). The graphs in Fig. 5.5 show the model results again for two scenarios (a) *Persistent ICE Petrol Dominance* and (b) *Establishing NGV Dominance*: the inherent attractiveness settings (i), their consequences for the social behavioral norm (ii) and the corresponding impact on the vehicle stock development (iii). The difference between the two scenarios (a) and (b) is again the period of increased inherent attractiveness for diesel ICEs, but now in the context of NGVs simultaneously entering the vehicle fleet. In scenario (a), the introduction is a long-term stagnation, in scenario (b), it is successful. The comparative attractiveness is assumed to be similar for all technologies and is kept constant again.

The breakthrough of NGVs does not happen in scenario (a), and of course, similar to our example before, it could be forced with a high inherent attractiveness of NGVs for a longer period. However, this example reveals a second possibility. The stronger presence of diesel ICEs in the vehicle fleet of scenario (b) by an extended high level of the inherent attractiveness, additionally weakens the norm of petrol ICEs. The new NGVs benefit from this, and achieve a long-term successful fleet penetration.

The example illustrates that the critical fleet share is higher on a direct transition path without any other competing drivetrain technologies. Additional alternative technologies with significant fleet penetration reduce the norm of the dominating technology, lowering the threshold value for the tipping point for each technology. This means that the critical mass and thus the transition process is path dependent;

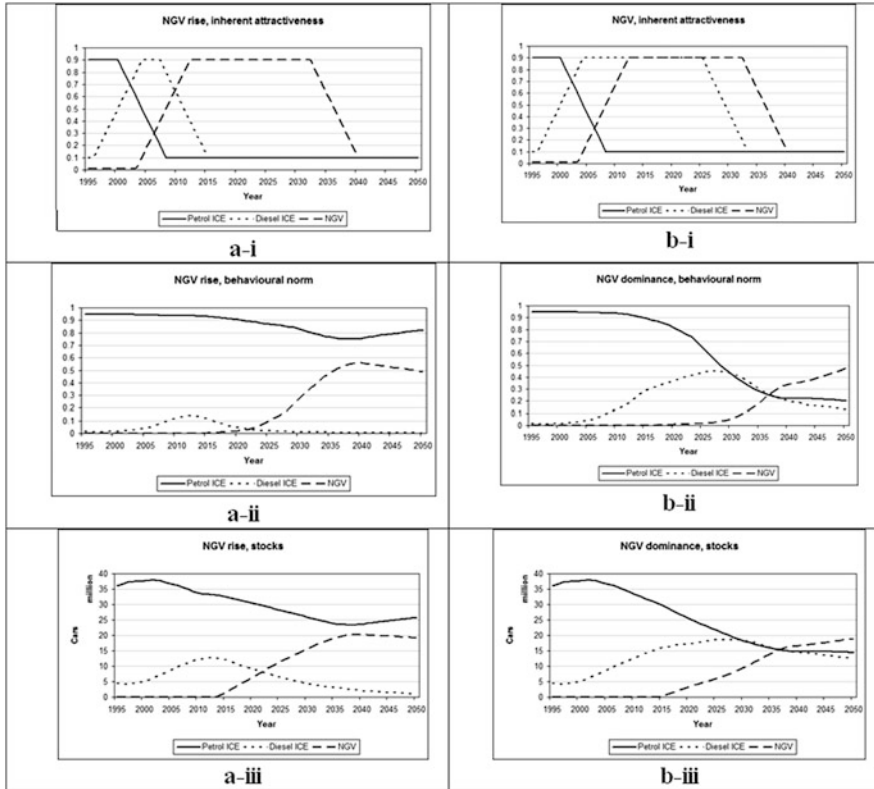


Fig. 5.5 A stronger diesel presence additionally weakens the dominating norm of petrol ICEs and enables NGVs to break through

it depends on historical technology substitution processes that have weakened the social behavioral norm of the dominant technology.

5.5 Model Analysis

A mathematical analysis of the System Dynamics (SD) model is helpful to enhance the understanding of the behavior patterns presented above and the nature of the critical mass (critical relative fleet shares). The analysis of the dynamics corresponding to the situation with two competing technologies was performed by Ulli-Beer et al. (2010). We build on this analysis and directly examine the case with three competing technologies. This analysis enables us to illustrate the model behavior with the intuitive analogy of a lightweight-ball rolling downhill (Ulli-Beer et al. 2010).

We introduce the short notation x_1 , x_2 , and x_3 for the normalized¹ vehicle stocks of the three drivetrain technologies, i.e., petrol ICEs, diesel ICEs and NGVs. In the absence of the third vehicle type x_3 , where we have the two groups of vehicles x_1 and $I - x_1 = x_2$, Ulli-Beer et al. (2010) have shown that the underlying dynamics can be formulated on the basis of a double well potential function $V(x_1)$:

$$\frac{dx_1}{dt} = -\frac{dV}{dx_1}$$

The mathematical analysis (see [Appendix](#)) shows that with three drivetrain technologies, we get the vehicle groups x_1 , x_2 and $I - x_1 - x_2 = x_3$, and two equations determining the potential function $V(x_1, x_2)$:

$$\begin{aligned}\frac{dx_1}{dt} &= -\frac{\partial V(x_1, x_2)}{\partial x_1} \\ \frac{dx_2}{dt} &= -\frac{\partial V(x_1, x_2)}{\partial x_2}\end{aligned}$$

Although there is no general global solution $V(x_1, x_2)$ for these two equations, we can find an approximated potential $U(x_1, x_2)$ for $(x_1, x_2) \in \mathbb{R}^2$ where $x_1 \geq 0$, $x_2 \geq 0$ and $x_1 + x_2 \leq I$. As Ulli-Beer et al. (2010) point out, the nonlinearity of the social norm influence creates the acceptance and rejection dynamics. Although, in reality the norm influences may correspond best with a s-shaped curve, the mathematical analysis is done with the simplest nonlinear example, a quadratic function. However, the qualitative results will not change when using an s-shaped social norm effect. If we further choose a very symmetric case of all parameters (i.e. the parameter value of the inherent and comparative attractiveness of each technology are the same), we get the following potential (see [Appendix](#)):

$$\begin{aligned}U(x_1, x_2) &= 0.4x_1 - 11.9x_1^2 + 23.6x_1^3 - 12.1x_1^4 + 0.4x_2 + x_1x_2 - 1.9x_1^2x_2 \\ &\quad - 11.9x_2^2 - 1.9x_1x_2^2 + 23.9x_1^2x_2^2 + 23.6x_2^3 - 12.1x_2^4\end{aligned}$$

A plot of this approximated potential U is shown in [Fig. 5.6](#). The dynamics of the model correspond to a lightweight-ball moving in the landscape defined by U . Its coordinates refer to the fleet shares (normalized stock values) of technologies 1 and 2. The fleet share of technology 3 is not directly accessible in a 3D-picture (a third dimension is needed to show the potential), but can easily be calculated as $I - x_1 - x_2 = x_3$. The fleet shares change when the ball is moving. It is not possible to move into the plateau region, because the highest fleet share possible is 100 %.

¹ Normalized to the total fleet stock $x_i = \frac{x_i}{x_1 + x_2 + x_3}$.

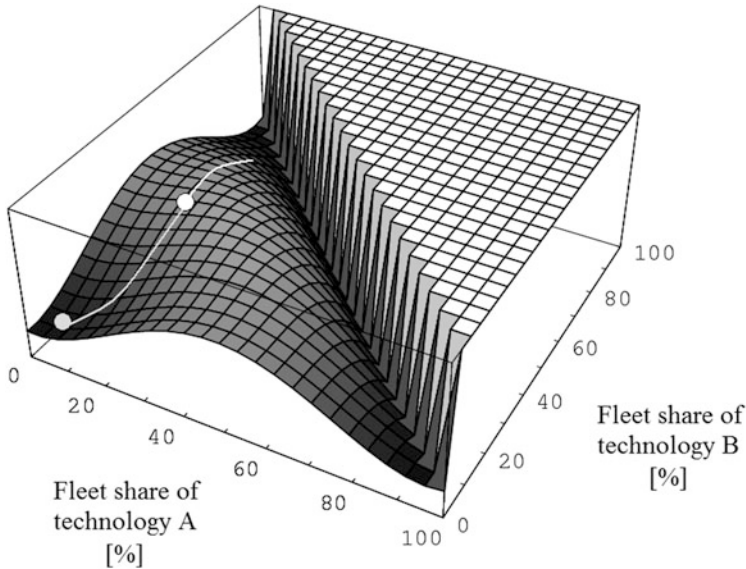


Fig. 5.6 Approximated potential in the case of three competing technologies with a quadratic socio-technical norm effect. A possible initial state of the system is symbolized by a *white ball*, rolling downhill along the *grey line* to the *grey ball's* position. This corresponds to the development of the system without any incentives or additional external influences. Another stable state other than the *grey* one can be reached when the system is lifted above one of the potential walls, for example, following the *white line* in the opposite direction

The local minima in the picture indicate stable states of the system. These are attracting points and the ball will move to one of those minima, depending upon where it is released. The minima correspond to preferred fleet share combinations, and the vehicle fleet will develop towards one of these combinations when it is not forced by external influences. The existence of local minima divides the area into different regions that are dominated by one of these stable states. All trajectories of the system starting in the same region end up in the same equilibrium. In Fig. 5.6, the initial state of the system is symbolized by a white ball. If the ball is released while the system parameters are kept constant (i.e., without external influence), it will move downhill along the grey line to the grey ball's position. Another stable state other than the grey one can only be reached when the system is lifted above one of the potential walls, for example, following the white line, entering the regime of another minimum. In other words, there are barriers separating these regions from each other. Crossing such a wall does always cause a complete change of the trajectory towards a new equilibrium. These walls represent the critical mass in the model. The minima emerge from the social norm mapping imitation effects.

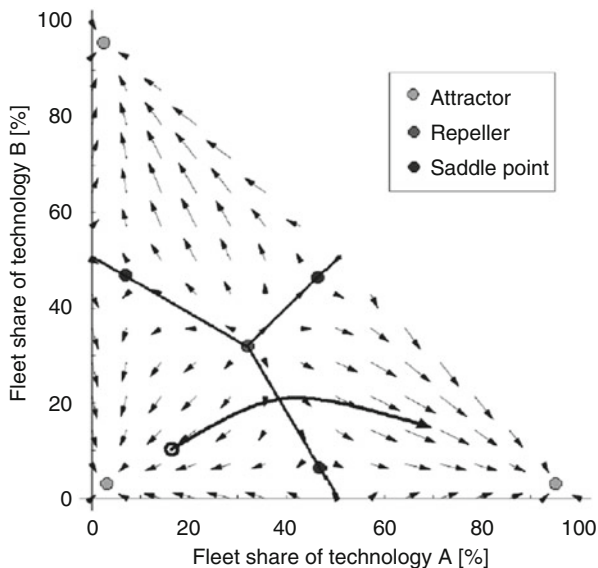


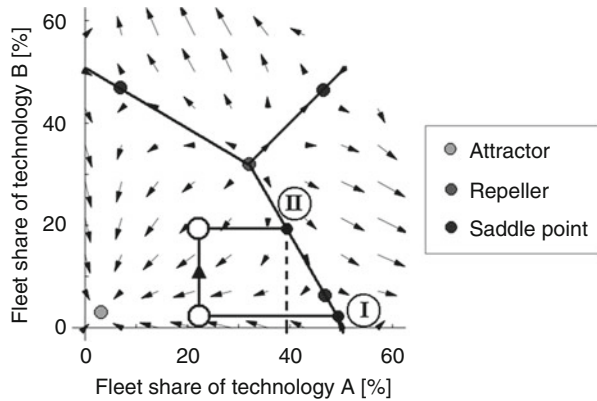
Fig. 5.7 Visualization of the driving ‘force field’ of the system without external influence. *Arrows* indicate the direction and velocity of movement. Coordinates are given as fleet shares. Connecting the central repeller with the saddle points reveals areas that are dominated by different drivetrain technologies. These connections represent the *critical mass* in the adoption process, i.e. a shift in the dominance of the socio-technical norm due to the nonlinear norm building process. If external influences force the system to move along the indicated pathway (*long arrow*), the critical mass is reached when crossing one of the straight lines

5.6 Discussion

The insights gained from model behavior and analyses are discussed in the following. To abstract the specifics of the case, we replace the names of the three competing drivetrain technologies with A, B and C. The system behavior can be described in the same way as in the mechanical lightweight-ball analogy. To visualize the driving forces of the socio-technical norm regime, Fig. 5.7 shows the top view of the area containing all possible system states where coordinates are given as fleet shares of technologies A and B, again with fleet shares $C = 100\% - A - B$. The small arrows indicate the direction and strength of the driving force if there are no external influences, revealing three local minima or stable states (attractors), three saddle points and one completely unstable point, a local maximum (repeller) in the center. The repeller corresponds to a fleet composition of one-third for each drivetrain technology, a very sensitive, unstable equilibrium.

Deviations from the central equilibrium lead into one of the three areas separated by straight lines. In our highly symmetric example (all technologies share the same general parameter settings), they are found by connecting the repeller to the three

Fig. 5.8 A transition to technology A's regime on two different paths, both starting in the lower white spot: Direct transition with 50 % critical adopter share for A, or a precedent increase in technology B's share from 2 % to 20 % (arrow), reducing the critical share for A to 40 %



saddle points. Each area comprises an attracting equilibrium point or local minimum. The local minimum near (0/0) is dominated by the third technology which cannot be shown in this graph but has the fleet share $C = 100\% - A - B$.

Policy-based consumer incentives, for example, may influence the purchase decision and move the system away from its equilibrium state. Crossing the boundaries means entering another technological *norm regime* and ending up with that dominant technology. If we look at an example trajectory (long arrow), the system must be forced by external influence to move against the intrinsic driving force. It reaches a tipping point when crossing the boundary line. Entering the *norm regime* of technology A determines the final state of the system, even if external influence is stopped. The coordinate of the point where the boundary is crossed corresponds to a critical adopter share for A. Obviously this coordinate may be varied depending on the systems trajectory. However, if the external influence is ceased *before* the boundary is crossed, the system moves back to the old equilibrium.

Most interesting is the case of three competing technologies, since it causes path dependency. As soon as there are three or more competing technologies, the critical mass depends on the path of the development. Figure 5.8 illustrates two path examples for the transition into a new regime. The Fig. 5.8 shows a picture detail of the driving force field. Moving the system from the lower white spot to the regime of technology A would require a fleet share of A of about 50 % (mark (I)). After that point the transition is self-sustaining and any incentive can be ceased. Technology B's fleet share is constant at some 2 %. However, if B's share is increased to 20 %, i.e. the system is first moved along the arrow, conditions change. The fleet share of technology B attacks technology C's dominance too, making it 'easier' for technology A to gain a critical share. The transition in horizontal direction only needs an adopter share of 40 % to become self-sustaining (mark (II)). If the transition to A on the lower path fails because the external influence is ceased early, the transition on the upper path could still be successful. We conclude that the cost and external influence needed is path-dependent. The development may become irreversible.

5.7 Conclusions

The purpose of the study is to clarify the link between green product diffusion and social norm building and to analyze resulting system behavioral effects. We establish an endogenous understanding on socio-technical norm effects on green product diffusion. We link the systemic phenomena of tipping point and path-dependency with the concept of social norm building and technology competition in markets. This provides a more detailed understanding of the dynamic processes behind green product diffusion. We argue that competition in the market is also a competition between socio-technical norms, specifically in cases of green product substitution.

We show that green product diffusion models should also include social norm effects to analyze the pathways of technology substitution. We propose a model that uses the social behavioral norm to map imitation effects. Social norm effects depend nonlinearly on the customers' perception of the corresponding drivetrain technology's stock. This nonlinear relationship makes the difference between an autocatalytic model, such as the Bass model which "is limited to describing only successful market diffusion into one stable state" (Ulli-Beer et al. 2010), and a model that maps adoption and rejection as well. The social norm dynamics of competing technologies provide the endogenous mechanisms of tipping behavior in s-shape diffusion models. This is in line with the understanding of the tipping point as a point of no return between rejection and adoption. It also substantiates the proposition that a diffusion model must incorporate a resistance to produce tipping behavior, as suggested by Phillips (2007).

In order to enhance the dynamic understanding of the observed behavior patterns we use the intuitive analogy of a lightweight-ball moving in a landscape (Ulli-Beer et al. 2010). A quadratic socio-technical norm effect generates a fourth degree potential function. Based on this mathematical representation, we can identify socio-technical norm regimes, which are interpreted as technological lock-in situations. These equilibrium states represent fleet shares of different drivetrain technologies that do not change over time without modifying the parameters. Since the system is always in the domain of one technology, i.e., in a technological lock-in, the other technologies are locked out. Breaking the lock-in situation is possible but, to change the norm regime, external influence is needed. These can also be co-evolutionary changes in the technological innovation systems, but those are excluded from our analysis. External influences by policy incentives force the system to move from its equilibrium state against the intrinsic driving force. The incentives can only be ceased if the new socio-technical norm becomes dominant and sustains the substitution process. The *relative* cumulative adopter share of the corresponding technology, which is needed for that is identified as the critical mass. The tipping point is understood as the moment where the critical mass is reached. Since policy incentives usually involve high costs, it is useful to know that the process has become self-sustaining and that incentives can be ceased. However, an early stop would lead to a transition failure and give rise to costs that do not have any long-term effect. The system would move back to its original equilibrium. In the long run, a new lock-in is inevitable. This analysis also confirms our argument, that

the circular causalities of socio-technical norm effects explain tipping behavior in green product diffusion (see *Research Question 1*).

Coming back to the *Research Question 2* we draw the following conclusions: A critical relative adopter share is needed to establish a new dominant social behavioral norm. The norm causes the existence of norm regimes (lock-in areas), and therefore the critical mass of adopters, as well as the tipping point. The tipping point marks the transition into a new norm regime, determining the final state of the system, if any external influence is stopped and no further changes are effective. In this situation, moving between norm regimes always requires external influence to reach the critical mass.

Concerning *Research Question 3* we conclude that the number of competing technologies causes path dependence. As soon as there are three or more competing technologies, the critical mass depends on the path of the development.

Finally we point out, that the model has a generic structure and can be used to describe technology substitution processes in a general context, where societal needs trigger social norm building. It also helps to identify the critical mass under different parameter setting, or boundary conditions, respectively. Understanding the effect of competing normative influences has important implications for entrepreneurs and policy makers that have to take long term investment decisions concerning green technologies. Social marketing policy measures may become cost-effective levers. Also, preference changes based on social norm influences may offer a new research perspective to traditional theories on the hazard of disruption in industries (Tellis 2008; Sood and Tellis 2011).

However, while the socio-technical norm dynamics may describe the diffusion pathway, other co-evolutionary (feedback) processes may be effective in further subsystem (e.g. learning-by-doing, standardization), that influence the shape of the socio-technical landscape and subsequently the diffusion pathway. These kinds of processes are not considered in our analysis. Nonetheless, they can be addressed as well with the illustrated simulation based theory building approach. Eventually, with increasing feedback complexity, the mathematical analysis may fall short – but the analogy may still remain helpful to build intuition.

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Appendix

Derivation of the Potential for the Three Competing Technologies

In Fig. 5.9, the stock and flow structure for drivetrain technology i is shown twice: the picture to the right introduces short names for the model variables which are used in the equations below. The index i represents one of the drivetrain technologies considered in the model.

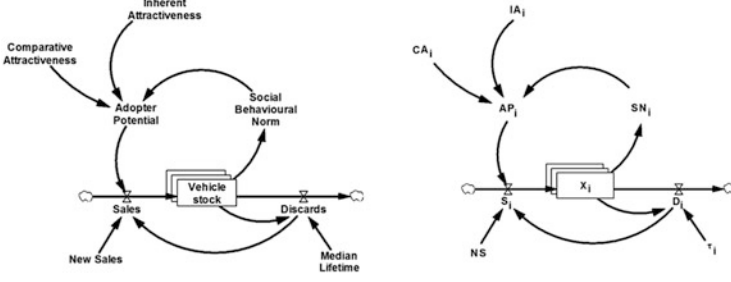


Fig. 5.9 Stock and flow structure as it is applied to every technology platform with abbreviated variable names.

In **Subsection 2**, we have introduced Eq. 5.2 of the rate for X_i , which reads

$$\frac{dX_i}{dt} = \frac{CA_i * (SN_i + IA_i - SN_i IA_i)}{\sum_k CA_k * (SN_k + IA_k - SN_k IA_k)} \left(\sum_j \frac{X_j}{\tau_j} + NS \right) - \frac{X_i}{\tau_i} \quad (5.3)$$

For simplification we

- Set the net new sales ns equal to 0, keeping the total number of vehicles in the fleet constant.
- Normalize Eq. 5.3 to the total number of vehicles N in the whole fleet: $x_i = \frac{X_i}{N}$. x_i represents the fleet share of technology i .
- Use the same lifetime τ for all drivetrain technologies.
- Assume that all involved technologies have the same comparative attractiveness. Therefore the term CA_i is cancelled out.

These simplifications yield

$$\frac{dx_i}{dt} = \frac{SN_i(1 - an_i) + IA_i}{\sum_k (SN_k(1 - IA_k) + IA_k)} \sum_j \frac{x_j}{\tau} - \frac{x_i}{\tau}. \quad (5.4)$$

The social norm SN_i is given as a function of the fleet share x_i . As Ulli-Beer et al. (2010) point out, that the behavioral norm should be represented by a nonlinear function. The easiest nonlinear case is a pure quadratic function (see the **Results** section and **Appendix**):

$$SN_i = f(x_i) = x_i^2$$

This yields

$$\frac{dx_i}{dt} = \frac{x_i^2(1 - an_i) + IA_i}{\sum_k (x_k^2(1 - IA_k) + IA_k)} \sum_j \frac{x_j}{\tau} - \frac{x_i}{\tau}.$$

In our 3-drivetrain system with constant fleet we have $x_3 = 1 - x_1 - x_2$ and therefore $\frac{dx_3}{dt} = -\frac{dx_1}{dt} - \frac{dx_2}{dt}$, leading to two independent rate equations:

$$\begin{aligned} \frac{dx_1}{dt} &= \frac{1}{\tau} \left(-x_1 + \dots \right. \\ &\dots + \frac{x_1^2(1 - an_1) + an_1}{x_1^2(1 - an_1) + x_2^2(1 - an_2) + (1 - x_1 - x_2)^2(1 - an_3) + an_1 + an_2 + an_3} \\ \frac{dx_2}{dt} &= \frac{1}{\tau} \left(-x_2 + \dots \right. \\ &\dots + \frac{x_2^2(1 - an_2) + an_2}{x_1^2(1 - an_1) + x_2^2(1 - an_2) + (1 - x_1 - x_2)^2(1 - an_3) + an_1 + an_2 + an_3} \end{aligned}$$

Following the lightweight-ball metaphor introduced by Ulli-Beer et al. (2010) and extending it to three competing technologies leads to the elegant form including a potential $V(x_1, x_2)$:

$$\begin{pmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \end{pmatrix} = -\nabla V(x_1, x_2) = \begin{pmatrix} -\frac{\partial V(x_1, x_2)}{\partial x_1} \\ -\frac{\partial V(x_1, x_2)}{\partial x_2} \end{pmatrix} \quad (5.5)$$

However, it is not possible to define a global potential $V(x_1, x_2)$, satisfying Eq. 5.5. This can easily be shown by calculating the rotation of the left-hand side.

Although no global potential $V(x_1, x_2)$ exists, we can find an approximated potential $U(x_1, x_2)$. For this purpose we use a general fourth order function of x_1 and x_2 of the following form:

$$\begin{aligned} U(x_1, x_2) &= a_1x_1 - a_2x_1^2 + a_3x_1^3 - a_4x_1^4 + b_1x_2 + fx_1x_2 - cx_1^2x_2 \\ &\quad - b_2x_2^2 - dx_1x_2^2 + ex_1^2x_2^2 + b_3x_2^3 - b_4x_2^4 \end{aligned}$$

There is no constant term because this would just cause a translation of the potential function, and can be omitted. We now insert $\tau = 15$ and $IA_i = 0.02$, for all i , and set up a homogeneous system of equations using the roots of the dynamic equations. Solving for the parameters $a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4, c, d, e, f$ leads to the approximated potential

$$\begin{aligned} U(x_1, x_2) &= 0.4x_1 - 11.9x_1^2 + 23.6x_1^3 - 12.1x_1^4 + 0.4x_2 + x_1x_2 - 1.9x_1^2x_2 \\ &\quad - 11.9x_2^2 - 1.9x_1x_2^2 + 23.9x_1^2x_2^2 + 23.6x_2^3 - 12.1x_2^4 \end{aligned}$$

Quadratic Versus S-Shaped Norm Function

To keep the mathematical analysis simple we used a quadratic function for the social behavioral norm. With a logistic function for SN_i , Eq. 5.4 would read

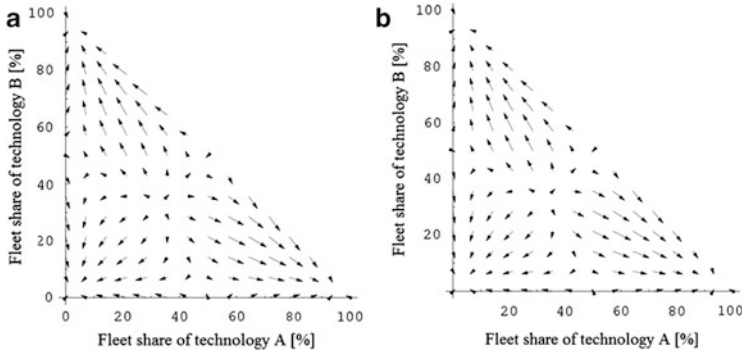


Fig. 5.10 Driving force field plot with a quadratic social norm function (a) and its equivalent with an s-shaped social norm function (b), here a logistic function

$$\frac{dx_i}{dt} = \frac{\frac{1-IA_i}{1+e^{-10(-0.5+x_i)}} + IA_i}{\sum_{k=1}^3 \left(\frac{1-IA_k}{1+e^{-10(-0.5+x_k)}} + IA_k \right)} \sum_{j=1}^3 \frac{x_j}{\tau} - \frac{x_i}{\tau}.$$

Without giving a profound analysis, we illustrate the similarity of the resulting potentials and behavior using the underlying force field as in Fig. 5.7. These are plotted in Fig. 5.10b for the s-shaped and in Fig. 5.10a for the quadratic norm function respectively. Qualitatively the two yield the same results in the area of interest.

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