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Diffusion Dynamics of Sustainable Innovation - Insights on Diffusion Patterns Based on the Analysis of 100 Sustainable Product and Service Innovations

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Abstract. There is a growing consensus about the urgent necessity to green the economy and to decouple economic growth from environmental pressure. Against this background, the article explores three questions: (1) What are key factors influencing diffusion dynamics of sustainable product and service innovations? (2) To what extent do diffusion processes of sustainable product and service innovations differ from each other, and can different groups of diffusion processes be identified? (3) Which factors, actors, and institutional settings are characteristic of different groups of diffusion processes?

While diffusion research on sustainable innovation so far has been limited to case studies with just one or a small number of cases or has been focused on individual sectors, the empirical data presented here cover a large number of cases from a broad variety of product fields. This allows for generalizations as well as relevant insights and conclusions for sustainability, environmental and innovation policies.

The empirical investigation of 100 sustainable product and service innovations revealed that diffusion processes of sustainable innovations differ substantially: The cluster analysis showed that five groups of sustainable innovations can be differentiated which differ significantly in terms of the factors influencing the diffusion process. The empirical results thus both support the assumption that different types of diffusion paths do in fact exist and also permit characterization of the various types of diffusion paths. The evolutionary concept of diffusion paths develops significant explanatory power on the basis of which faster or slower cases of diffusion and the success or failure of sustainable innovations can be better understood.

Keywords. Innovation, Diffusion of innovations, Sustainable development, Environmental protection, Comparative analysis, Evolutionary economics, Path concept.

1 Introduction

There is overwhelming evidence that mankind has become a geological force (Crutzen, 2002) and that we are overloading the Earths's carrying capacities. Rockström et al. (2009) explored planetary boundaries and conclude, "Anthropogenic pressures on the Earth System have reached a scale where abrupt global environmental change can no longer be excluded." (Rockström et al., 2009, p. 1) Despite the fact that there has been an intensive political as well as scientific debate about the concept of sustainable development for more than 20 years (United Nations, 2012), even today not a single nation on the planet can claim to be sustainable in the sense that it provides for human well-being within Earth's carrying capacities (United Nations Environment Programme (UNEP), 2011, p. 21). Many countries enjoy a high level of human development – but at the cost of a large ecological footprint (Burns et al., 2010). Others have a very small footprint, but face urgent needs to improve access to basic services such as health, education, and potable water (Malik, 2013).

Against this background, there is a growing consensus about the urgent necessity to green the economy and to decouple economic growth from environmental pressure (Organisation for Economic Co-operation and Development (OECD), 2011). Greening the economy requires a strategy for sustainable transitions and fundamental changes in production and consumption patterns (UNEP, 2011). One key element in promoting and managing the multilevel challenge of sustainable transitions (Geels, 2010) is the development, implementation, and diffusion of radically new or significantly improved products (goods or services), processes, or practices which reduce the use of natural resources and decrease the release of harmful substances across the whole life cycle (Eco Innovation Observatory (EIO), 2013, p. 2). Thus, sustainable innovation and its diffusion are a key strategy for a societal transformation process toward sustainable development and a green economy. Understanding of diffusion of sustainable innovations recently has gained more importance given the fact that some sustainable innovations are already at a mature stage (Karakaya, Hidalgo & Nuur, 2014).

The central problem – and this is the evaluation of the status quo on which the present study is based – is not a lack of sustainable innovations, but that their diffusion throughout the economy and society is too narrow and too slow to solve the urgent challenges of sustainability such as climate protection and resource conservation. In other words: from a sustainability perspective, we are not confronted primarily with a problem of innovation, but a problem of diffusion!

Against this background the objective of this work is to contribute to the clarification of the following questions:

- What are key factors influencing diffusion dynamics of sustainable product and service innovations?
- To what extent do diffusion processes of sustainable product and service innovations differ from each other, and can different groups of diffusion processes be identified?
- Which factors, actors, and institutional settings are characteristic of different groups of diffusion processes?

This article will explore these questions by presenting and discussing the results of an empirical study of 100 cases of diffusion of sustainable products and services from ten different sectors. In the first part of the paper, we develop a conceptual framework for investigating the diffusion of sustainable product and service innovations. In Section 3 we define the unit of analysis, present the guiding research questions, and explicate the methodology of our empirical investigation. The methodological approach of the empirical study is innovative because it blends case study methodology using process-generated data with statistical identification of factors and clusters. In the following part of the paper (Section 4) we present the correlation and results from the factor analysis as well as the results from the cluster analysis. Based on these results we characterize five different clusters of diffusion of sustainable innovation. In the final part of paper we draw conclusions with regard to the guiding research questions, describe the limitations of the study, and outline further research needs.

2 Conceptual framework

Based on an extensive literature review, in the following section we will clarify the term "sustainable innovation" and present key insights from diffusion research in regard to factors influencing the adoption rate of innovation in general and sustainable innovation in particular. Building on central concepts of sustainable innovation and diffusion research, we then develop a conceptual framework for the analysis of the diffusion of sustainable innovation. We do this by drawing on insights from evolutionary economics in the construction of a path concept of diffusion, by providing a concept of how changes in the diffusion path come about, by looking at possibilities for assessing environmental effects of diffusion processes, and finally by pulling these elements together in a conceptual framework for the empirical investigation of the diffusion of sustainable product and service innovations.

2.1 Sustainable innovation

Sustainability-oriented innovation and technology studies have received increasing attention over the past 10 to 15 years (Markard et al., 2012, p. 955). The importance of sustainable innovation management is growing both in practice and in academia (Schiederig et al., 2012). What exactly is meant by "sustainable innovation"? Numerous terms to describe similar phenomena have been used widely in academia. The key terms used since the mid-1990s include "environmental innovation" and "eco-innovation" (Fussler, 1996; Rennings, 2000; Kemp & Pearson, 2007; Jänicke 2008; OECD, 2009; Gerstlberger & Will 2010, Horbach et al., 2012), "sustainability innovation" (Fichter & Pfriem, 2007; Arnold & Hockerts, 2011; Belz, Schrader & Arnold, 2011), "sustainable innovation" (Wüstenhagen et al., 2008; Nill & Kemp, 2009; Hockerts & Wüstenhagen, 2010), "sustainability-oriented innovation" (Klewitz & Hansen, 2014), and "green innovation" (Schiederig et al., 2012). While a distinction between social and environmental issues in innovation is made to some extent, a clear line is difficult to draw. A recent analysis of 8,516 journal publications shows that "40.7% (3,469) apply the notion 'environmental innovation', 31.9% (2,716) the notion 'sustainable innovation', 17.6% (1,495) 'eco-innovation' and 9.8% (836) the notion 'green innovation'. It appears that more than 80% of the publications use only one notion, indicating that the notions are used consistently within individual publications." (Schiederig et al., 2012, p. 183) The analysis shows that three different ideas of green, eco/ecological, and environmental innovation are used largely synonymously, while the notion of sustainable innovation broadens the concept and includes a social dimension.

There has been a rich debate in the economic literature about the distinctive features of environmental innovations and eco-innovations as opposed to general innovations

(Rennings, 2000). One of the most referenced definitions is provided by Kemp and Pearson (2007): "Eco-innovation is the production, application or exploitation of a good, service, production process, organizational structure, or management or business method that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of resource use (including energy use) compared to relevant alternatives". (Kemp and Pearson, 2007, p. 7). The EU-funded Eco-Innovation Observatory (EIO) describes eco-innovation as "any innovation that reduces the use of natural resources and decreases the release of harmful substances across the whole life-cycle" (EIO, 2013, p. 10). This broad definition builds on an existing understanding of innovation and emphasizes types of inputs, outputs, as well as full life-cycle impact as key indicators of eco-innovation. Concepts of sustainable or sustainability innovation include these ecological aspects as a key feature, but also explicitly claim that radically new or significantly improved products (goods or services), processes, or practices should contribute to economic and social goals of sustainable development (Wüstenhagen et al., 2008). Rather than just focusing on short-term profits, stakeholders expect firms to meet a triple bottom line of economic, environmental, and social value creation (Elkington, 1999; Schaltegger & Wagner, 2011). Against this background, Fichter (2005) defines sustainable innovation as "the development and implementation of a radically new or significantly improved technical, organizational, business-related, institutional or social solution that meets a triple bottom line of economic, environmental and social value creation. Sustainable innovation contributes to production and consumption patterns that secure human activity within the Earths's carrying capacities." (Fichter, 2005, p. 138) In this paper we will follow this concept of "sustainable innovation."

2.2 Diffusion research

While "innovation" is the process of developing and implementing a radically new or significantly improved solution, we define "diffusion" as the process of imitation and adaptation of an innovation by a growing number of adopters. It comprises the period after the first successful implementation or after market introduction.

With regard to key factors influencing diffusion dynamics, diffusion research offers a vast array of concepts and empirical studies that deal with diffusion processes in general as well as with factors influencing the adoption rate of sustainable innovation in particular (Clausen et al., 2011, Karakaya, Hidalgo & Nuur, 2014). Rogers's pioneering work on diffusion processes underlines the importance of the attributes of innovations. Rogers (2003, p. 219 ff.) indicates that the relative advantage, compatibility, complexity, trialability, and observability of an innovation are important variables that can influence the speed of adoption. When these attributes are applied to the diffusion of sustainable product innovations, they can be considered to be relevant product-related variables. For these reason, they were used as product-related factors for examining diffusion paths of sustainable innovations.

Besides product-related variables, adoptor-related factors also play an important role in explaining the diffusion of innovations. It appears established that the adoptor group of "innovators" plays an important role during market introduction and in the first phase of diffusion, and this holds for both individuals (Rogers, 2003) and organizations (Gurisatti et al., 1997; Mukoyama, 2003). In reference to the adoptor-related factors affecting the diffusion trajectory, the question of the "presence" and participation of user-innovators as well as their early involvement in the innovation process seem to play important roles (Baldwin, Hienerth & von Hippel, 2006; Lüthje & Herstatt, 2004). The necessity of behavior changes and the requirement to develop new (consumption) routines inhibit the diffusion of innovations (Konrad & Nill, 2001; Scholl, 2009). Uncertainties concerning the function and the quality of the product, but also the regulatory environment of an innovation, delay the adoption process in the case of individuals as well as businesses (Hintemann, 2002). Fundamental differences seem to exist between private individuals and businesses as adoptors when it comes to decision-making and in the relative importance of cost-effectiveness and liquidity. In businesses, decisions are usually made collectively, and companies tend to value function, quality, and cost-effectiveness more highly (Mukoyama, 2003). In contrast, the price plays a lesser role if cost-effectiveness is given, even if SMEs (small and medium-sized enterprises) routinely mention limited availability of capital when surveyed concerning obstacles to adopting innovations (Hitchens et al., 2004). In the case of private individuals, on the other hand, a high price is often a constraint even independently of cost-effectiveness because of limited liquidity (Bottomley and Fildes, 1998; Andrews & DeVault, 2009).

Concerning supplier-related factors, various authors point to the role of pioneering suppliers of innovations (Wüstenhagen et al., 2008; Hockerts & Wüstenhagen, 2010), whereby their orientation toward sustainability could also play a role in the context of sustainability. Suppliers' sizes and reputations are important, besides the availability of relevant products and services on the market (Barney, 1991; Fombrun, 1996; Shapiro & Varian, 1999). Against this background, the variables (sustainability) goals of innovators, size and reputation of innovators, and the completeness and availability of products and services on the market can be considered to be relevant factors potentially influencing diffusion dynamics.

Concerning suppliers, Nelson (1994) in particular also refers to the development of supporting structures within the sector, so sector-related factors could be relevant for the analysis as well. The existence and activities of industry trade associations appears to be relevant especially in the context of obtaining financial support from the government, reducing regulatory obstacles, or developing exnovation tools for phasing out predecessor products (Nelson, 1994; Bruns, Köppel, Ohlhorst, & Schön, 2008). The role of market leaders also appears to be relevant for diffusion. For example, whether they spend years litigating against laws promoting renewables or whether innovators in the field in question are involved from the beginning can be expected to have a significant impact on the speed of diffusion. Intermediaries as change agents should also be taken into consideration as a possible supporting factor (Antes & Fichter, 2010).

Because of the double externality problem of environmental innovations, the political factors of government intervention play a special role in their development and diffusion (Jänicke, 2008, 2005; Rennings, 1998). The diverse political instruments used by governments to support the diffusion of environmental innovations (Jänicke, 2008) as well as the societal forces impacting innovation and diffusion processes can be grouped in four different factors: governmental push and pull activities as well as institutional obstacles (Andersen & Liefferink, 1997; Jaffe & Stavins, 1995), lead market policies (Beise & Rennings, 2005), media reporting, and campaigns by non-governmental organizations (Brunner & Marxt, 2013).

Furthermore, diffusion research based on evolutionary economics also stresses the fact that there is an inherent dynamic in the diffusion path because of path dependencies, competing industry standards, and dominant designs (Nelson & Winter, 1982; Brown, Hendry & Harborne, 2007), and due to self-reinforcing effects such as the critical mass phenomenon (Arthur, 1989; Cowan, 1990; Lehmann-Waffenschmidt & Reichel, 2000, p. 349) or network effects (Geroski, 2000; Rogers, Medina, Rivera & Wiley, 2005; Vollebergh & Kemfert, 2005). The path-specific factors include the historical ties and self-reinforcing forces with effects on (routine) paths to date, the effects of price developments (up or down), and the forces resulting in new ties when new paths are established. Against this background, we constructed three path-specific factors to examine the diffusion paths of sustainable innovations: path dependencies due to historical ties, interactions between competing diffusion paths, and self-reinforcing effects within the diffusion path itself.

Based on theoretical and empirical work on factors influencing the diffusion process, six key areas of influence on diffusion speed can be distinguished: (1) product-related factors, (2) adoptor-related factors, (3) supplier-related factors, (4) sector-related factors, (5) government-related factors, and (6) path-related factors. Within the key areas, different factors have been identified (Clausen, Fichter & Winter, 2011).

2.3 Path concept of diffusion

When it comes to explaining why the diffusion speed of sustainable innovations does differ and what the key factors influencing diffusion dynamics are, evolutionary economics is a powerful theory to build on. During the past 30 years, numerous authors have placed the path concept developed in evolutionary economics at the center of their studies and approaches for explaining innovation and diffusion trajectories, using the work by Nelson and Winter (1982) as a starting point (Clausen et al., 2011). The path concept provides a good basis for studying existing path dependencies, potential exit options for creating new paths (Sydow, Schreyögg & Koch, 2009), and the factors emerging over the course of the diffusion process. To date, studies of trajectories have considered linear chains of events, bifurcation and multifurcation points, and linkages between different paths (Lehmann-Waffenschmidt & Reichel, 2000; Lehmann-Waffenschmidt, 2010). While lock-in to a particular path and the path dependencies that arise or have an effect here are discussed intensely, the questions as to how and why bifurcation and multifurcation points emerge and how actors can intentionally create new paths have received little attention. Precisely at this point, however, creating a link to the insights and conceptualizations of innovation process research appears promising (Van de Ven, 1999) because it deals with the emergence and the trajectories of innovation processes. In order to be able to create this linkage, however, it is vital to first make clear that innovation is a specific mode of transformation, and just one of several possible modes. Fundamentally speaking, four modes of transformation can be differentiated, and all of them are relevant for the sustainability of innovations (Fichter, 2014):

1. *Variation*: Gradual changes to existing technologies and practices optimize the path. Schumpeter characterizes this mode of transformation as "adaptive response" (Schumpeter, 1947).
2. *Innovation*: the attempt to achieve a lock-in break in a routine path. In the successful case of "breaking away" from a routine path, a split (bifurcation or multifurcation) occurs, and a new path is formed (path creation). Schumpeter characterizes this mode of transformation as "creative response" (Schumpeter, 1947).
3. *Diffusion* by imitation and adaptation: Innovative solutions already being used successfully in other regions, markets, or organizations are taken on and adapted. A relatively young path is broadened and disseminated; chains of events (imitation and adaptation processes on the part of specific adoptors) within this path branch out further and multiply. In part, however, innovative solutions are also adapted and varied in specific ways.
4. *Exnovation*: Previously used technologies, products, or practices are discontinued or phased out. A previous path is terminated. Examples include the ban on light bulbs in the European Union, Germany's nuclear phase-out, and decisions by companies to withdraw products from the market due to unprofitability or insufficient turnover.

The path conceptions existing to date do not differentiate between the four modes of transformation described above, even though it is precisely these four modes that provide an explanation of how bifurcation and multifurcation points can occur. Understanding the dynamics of sustainable innovation requires a further move to "interdisciplinary crossovers" (Geels, Hekkert & Jacobsson, 2008, 527). On the basis of the fundamental understanding presented above, an innovation path can be interpreted from an interdisciplinary standpoint as an innovation process and thus as an intentionally organized process for branching out from routine paths. Hence, an innovation path encompasses the chain of events of an innovation project. Extending the concept of the innovation path, a diffusion path can be understood as a chain of events of a particular diffusion process over time. The diffusion path includes the imitation and adaptation events on the part of the adoptors as well as the activities and measures affecting those adoptors, including, for example, the activities of suppliers, the services provided by market intermediaries (e.g., wholesalers and retailers) and policy intermediaries (e.g., energy or climate protection agencies) (Antes & Fichter, 2010) as well as, for instance, the efforts on the part of the government to intervene in the form of legal provisions and support programs. Thus, the diffusion path is embedded within a diffusion system which, as a social system (Rogers, 2003, p. 23 ff.), encompasses both diffusion-relevant actors and specific institutional arrangements. Against this background, we defined the term "diffusion path" as follows:

> *A diffusion path encompasses the chain of events of a certain diffusion process over time and its embeddedness in a specific diffusion system. It depicts the diffusion of an innovative solution by means of imitation and adaptation and can be caused by the efforts of actors to stabilize a new path and to establish it long-term or by self-reinforcing effects.*

2.4 Conceptual framework for the analysis of the diffusion of sustainable innovation

We used the diffusion path concept developed above to analyze the diffusion of sustainable innovation. On that basis we defined a diffusion path as the chain of events of a certain diffusion process. A diffusion path is embedded in the diffusion system of a specific region or sector and influenced by its actors, institutions, and resources (Geels et al., 2008). We distinguished six key areas of influence on diffusion speed on the basis of theoretical and empirical work on factors influencing the diffusion process (cf. Section 2.2): (1) product-related factors, (2) adoptor-related factors, (3) supplier-related factors, (4) sector-related factors, (5) government-related factors, and (6) path-related factors. A total of 22 variables potentially influence diffusion dynamics and were taken into account when analyzing diffusion dynamics. Major qualitative changes in the direction or speed of diffusion can be classified as tipping points (market introduction of a product, reaching critical mass, bifurcation or multifurcation points, change of direction and abrupt changes in the trajectory and market exit of the product) (Schelling, 1971, p. 181 ff.; Granovetter & Soong, 1986; Coenen, Benneworth & Truffer, 2012; Hess, 2014).

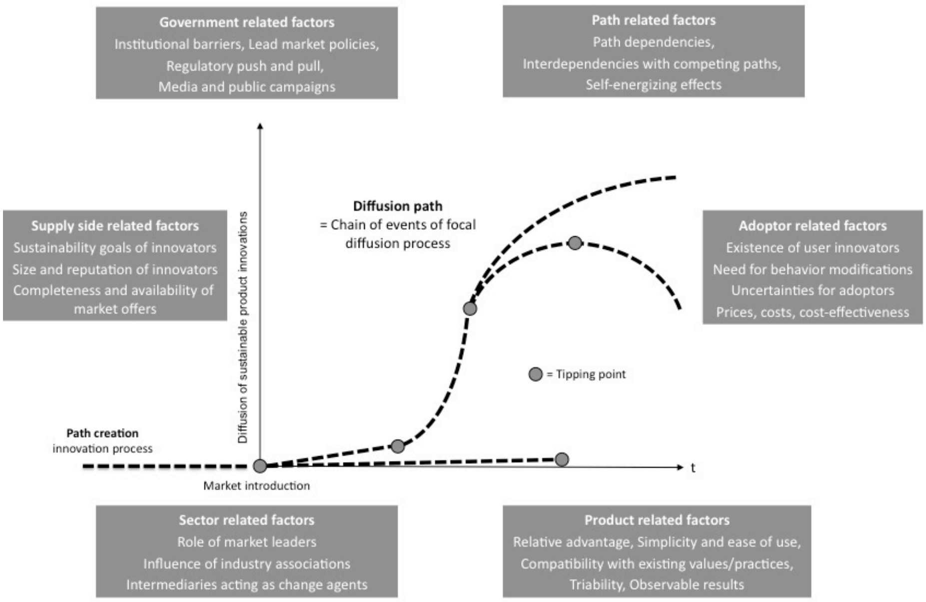

Fig. 1. Research framework for analyzing the diffusion of sustainable innovation

3 Material and methods

In the following section we give a precise definition of the unit of analysis employed in the empirical investigation, introduce the guiding research questions, and describe the methodology of our empirical research design.

3.1 Unit of analysis

The unit of analysis of the empirical investigation presented in this paper is diffusion dynamics of sustainable product and service innovations. Since diffusion processes are very complex fields of investigation, we limited the scope of the study in three ways. (1) We decided to focus on product and service innovations. We did this for two reasons: First, because products and services have a huge impact on production and consumptions patterns and on achieving economic, environmental, and social goals. Second, because the diffusion of marketable goods can be observed more easily (e.g. based on market data and other publicly available information) than process-related, institutional, or social innovation. This is especially important when investigating a large number of cases. (2) Furthermore, we decided to investigate the diffusion process in a specific geographical region or country. Because of funding constraints (cf. Acknowledgements), we decided to choose a European country and selected Germany as the largest national market in Europe. (3) Finally, we decided to focus the analysis on the period between market introduction and the time of investigation (2011). In order to study the diffusion process sufficiently, we defined that the duration between market introduction and the time of investigation had to be at least three years. Thus, we chose only products that had been introduced to market before 2008.

3.2 Guiding research questions

The guiding research questions for the empirical investigation are:

1. What are key factors influencing diffusion dynamics of sustainable product and service innovations?
2. To what extent do diffusion processes of sustainable product and service innovations differ from each other, and can different groups of diffusion processes be identified?
3. Which factors, actors, and institutional settings are characteristic of different groups of diffusion processes?

3.3 Methodology

Since no large-scale study across sectors or product fields on the diffusion of sustainable innovations has been conducted to date, this study broke new ground for empirical research. Two different methodological approaches were available for this task:

The first approach would attempt to study the diffusion of a marketable good (product or service innovation) across a long period of time, using selected indicators such as market share, parallel to the process itself. Such a longitudinal study was not feasible in the context of the 3-year duration of the project on which the present study is based because it would have required an observation period of more than three years. A second, alternative approach would be to model the diffusion of an innovation retrospectively using process-generated data, i.e., using authentic data created over time and for purposes other than answering the research questions formulated here. Such data covering long periods of time are often not available, or not in the quality desirable for purposes of research, for which reason such a procedure was out of the question here as well. In order to do justice to the present research problem nonetheless, we selected a research approach that encompasses a new form of methodological triangulation and which must therefore be briefly described and justified:

As sufficient data generated during the process itself are not available for the object of this study – diffusion of sustainable innovations – we decided on the following procedure for surveying data.

Selection of cases. First, we selected all those product fields from the universe of all marketable goods that are of particular importance for sustainable development and that can make a major contribution to reaching national and international sustainability goals. We used studies and sustainability strategies at the national and international levels for this purpose. The selection of product fields was to refer to the geographical area selected for the study (Germany). Both the lead markets and the fields already identified in German and European environmental and innovation policy were to be taken into account. They include the lead markets for environmental technology mentioned in the Umwelttechnologie-Atlas für Deutschland (Environmental Technology Atlas for Germany) "GreenTech made in Germany 2.0" (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), 2009) as well as the future markets for environmental innovations identified by the European Commission in the EU Lead Market Initiative (Commission of the European Communities (COM), 2007). When selecting cases, it was important to ensure that a sufficient range of products and services were covered in order to guarantee that the study actually included numerous sectors and product fields. Against this background, we decided to study at least 10 different product fields. Thus, we oriented sampling toward the main criteria: relevance for sustainability and range of the product fields.

In addition, the goal was to ensure that it would be possible to study a certain range of different products, services, and technologies in each product field in order to be able to elaborate possible commonalities and differences within each one. Against this background, we decided to use 10 different products from 10 different product fields for the study (cf. Table 2).

Defining independent variables. We performed a comprehensive evaluation of the literature as the basis for the empirical study. It yielded 22 potential factors influencing the diffusion trajectories of sustainable innovations in six fields of influence (cf. Section 2.2 and Figure 1) for which it can justifiably be assumed that they have an influence on the diffusion trajectories of sustainable product and service innovations or correlate with the dynamics of diffusion. We used these 22 potential factors as independent variables for the empirical study. We developed a coding system for each factor to assess the value of the variable (cf. Appendix 1).

Construction of the dependent variable "diffusion dynamics". One of the key goals of the study was to elaborate obstacles and drivers in the diffusion process, so we had to assess the progress of the diffusion process in this regard. Market penetration, i.e., market share, is most useful as a measure of diffusion of marketable goods. The amount of time required for the process, measured as the time since market entry, is relevant as well. Finally, a study across sectors and product fields must consider that a comparison across product fields cannot be carried out readily because of their very different underlying conditions. For this reason, the typical innovation and market cycles of a product field must be taken into account when constructing a dependent variable to be used as an indicator of diffusion dynamics across product fields.

That is why we drew upon three sub-indicators when constructing the indicator "diffusion dynamics." We defined them as follows with regard to the sample to be studied:

(1) Market share, using the scale:

a. up to 1% (coded as 1)

b. more than 1 and up to 10% (coded as 2)

c. more than 10 and up to 50% (coded as 3)

d. more than 50% (coded as 4)

(2) Duration of the diffusion process, measured as the time since market introduction:

a. before 1980 (coded as 1)

b. from 1980 to 1989 (coded as 2)

c. from 1990 to 1999 (coded as 3)

d. since 2000 (coded as 4)

(3) The diffusion speed of a specific innovation in relation to the other innovations in the product field in question. We set the two values mentioned above for a particular innovation in relation to the values of the other innovations in the product field, thus generating a ranking order. After all, what constitutes "rapid" diffusion varies considerably depending on the product field. The goal of adding 2 points to the value or subtracting 2 points from it was to enhance the value of the two most successful innovations in each product field and to reduce it for the two least successful ones. In individual product fields where it appeared impossible to differentiate reasonably between the three top innovations, we applied this method to the top or bottom three innovations. In other product fields, where the gap between the top or bottom two innovations was so large that it appeared unreasonable to assign them the same values, we did so for just the one top or bottom innovation. Table 1 shows the classification, Table 2 the results. The variable "diffusion dynamics" results from the summation of the values of the sub-variables market share, duration of diffusion process, and rank of a specific product/service within the product field. The minimum value of the variable "diffusion dynamics" is 0 (no dynamics), the maximum value is 10 (very high dynamics).

Table 1. Assessment of the rank of a specific product/service within the product field

Product field	**2 points subtracted from value**	**2 points added to value**
Organic food	Max. 1% market share	More than 10% market share
Renewable resources	Max. 10% market share and market introduction before 1990	More than 50% market share
Renewable energy systems	Max. 10% market share and market introduction before 1990	More than 50% market share or more than 10% market share and market introduction after 1980
Low-exergy energy systems	Max. 10% market share and market introduction before 1980 or max. 1% market share and market introduction before 1990	More than 10% market share
Energy-efficient electric devices and lighting	Max. 10% market share and market introduction before 1990	More than 10% market share and market introduction after 2000 or more than 50% market share and market introduction after 1990
Construction and heating technology	Max. 10% market share and market introduction before 1990	More than 10% market share and market introduction after 1990
Green IT end devices	Max. 10% market share	More than 10% market share and market introduction after 2005
Energy efficiency in data centers	Max. 10% market share and market introduction before 2005	More than 10% market share and market introduction after 2000
Telecommunications and online media	Max. 10% market share and market introduction before 2000	More than 10% market share and market introduction after 2000 or more than 50% market share and market introduction after 1990
Sustainable mobility	Max. 1% market share and market introduction before 1990	More than 10% market share

Table 2. Construction of the dependent variable "diffusion dynamics"

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
Organic food	Organic baby food	1969	1	50 to 100%	4	+2	**7**
	Bionade (organic soft-drink brand)	1995	3	1 to 10%	2	0	**5**
	Organic food subscriptions	1985	2	0 to 1%	1	-2	**1**
	Organic wine	1965	1	0 to 1%	1	-2	**0**
	Organic bread	1991	3	1 to 10%	2	0	**5**
	Fair trade coffee	1992	3	1 to 10%	2	0	**5**
	MSC-certified fish	1997	3	10 to 50%	3	+2	**8**

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
	Free-range eggs	1990	3	1 to 10%	2	0	**5**
	Organic milk	1991	3	1 to 10%	2	0	**5**
	Tea from the Teekampagne	1985	2	1 to 10%	2	0	**4**
Renewable resources	Starch-based biodegradable packaging	2005	4	0 to 1%	1	0	**5**
	Natural fiber plastic composites	1990	3	1 to 10%	2	0	**5**
	Biogenic lubricants	1999	3	1 to 10%	2	0	**5**
	Insulating materials from renewable resources	1982	2	1 to 10%	2	-2	**2**
	Natural paints	1980	1	1 to 10%	2	-2	**1**
	Wood-plastic composite (WPC) deck flooring	2004	4	1 to 10%	2	0	**6**
	Laundry detergents based on renewable resources	1985	2	50 to 100%	4	+2	**8**
	Organic cotton	1990	3	0 to 1%	1	0	**4**
	Woolen rugs with the Rugmark/Goodweave seal	1995	3	1 to 10%	2	0	**5**
	Organic shoes	1990	3	1 to 10%	2	0	**5**
Renewable energy systems	Biodiesel	1990	3	1 to 10%	2	0	**5**
	Biogas facilities	1980	2	10 to 50%	3	+2	**7**
	Large-scale hydroelectric facilities	1880	1	50 to 100%	4	+2	**7**
	Small-scale hydroelectric facilities	1980	2	50 to 100%	4	+2	**8**
	Pellet heating systems	1998	3	1 to 10%	2	0	**5**
	Photovoltaics	1985	2	1 to 10%	2	-2	**2**
	Skysails	2005	4	0 to 1%	1	0	**5**
	Thermal solar power	2007	4	0 to 1%	1	0	**5**
	Wind power (onshore)	1975	1	10 to 50%	3	0	**4**
	Wind power (offshore)	1991	3	0 to 1%	1	0	**4**
Low-exergy energy systems	Solar-powered absorption refrigeration systems	1960	1	0 to 1%	1	-2	**0**
	Small-scale cogeneration plants	1880	1	10 to 50%	3	+2	**6**
	Bioenergy villages	2005	4	0 to 1%	1	0	**5**
	Geothermal and hydrothermal cooling	1995	3	0 to 1%	1	0	**4**
	Long-term thermal energy storage	1995	3	0 to 1%	1	0	**4**
	Mobile heat transport	2009	4	0 to 1%	1	0	**5**
	District heating	1880	1	10 to 50%	3	+2	**6**

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
	Solar thermal energy	1978	1	1 to 10%	2	-2	**2**
	Deep geothermal facilities	1984	2	0 to 1%	1	-2	**1**
	Heat pumps	1975	1	10 to 50%	3	+2	**6**
Energy-efficient electric devices	Highly efficient freezers	2004	4	10 to 50%	3	+2	**9**
	Highly efficient refrigerators	2004	4	1 to 10%	2	0	**6**
	Highly efficient clothes dryers	1998	3	1 to 10%	2	0	**5**
	Energy-saving light bulbs	1985	2	1 to 10%	2	-2	**2**
	Highly efficient dishwashers	1999	3	50 to 100%	4	+2	**9**
	Induction cookers	1987	2	1 to 10%	2	-2	**2**
	LED lighting fixtures	2007	4	1 to 10%	2	0	**6**
	Master-slave multiple-socket outlets	2000	4	1 to 10%	2	0	**6**
	Highly efficient circulation pumps	2000	4	1 to 10%	2	0	**6**
	Highly efficient washing machines	1998	3	50 to 100%	4	+2	**9**
Construction and heating technology	Passive houses	2000	4	1 to 10%	2	0	**6**
	Prefabricated wood building	1920	1	10 to 50%	3	0	**5**
	Composite insulation systems	1957	1	1 to 10%	2	-2	**1**
	Heat recovery ventilation	1970	1	1 to 10%	2	-2	**1**
	Windows with triple glazing	1990	3	50 to 100%	4	+2	**9**
	Condensing boilers	1990	3	10 to 50%	3	+2	**8**
	Underfloor and wall heating	1980	2	10 to 50%	3	0	**5**
	Radiator thermostats	1969	1	50 to 100%	4	0	**5**
	Time-controlled thermostat	1999	3	1 to 10%	2	0	**5**
	Hydronic balancing	1970	1	10 to 50%	3	0	**4**
Green IT end devices	Inkjet printers	1984	2	50 to 100%	4	0	**6**
	Multifunctional devices	1994	3	50 to 100%	4	0	**7**
	80-plus power supply units	2005	4	50 to 100%	4	+2	**10**
	2 ½" hard disks	1992	3	50 to 100%	4	0	**7**
	Windows energy options	1995	3	1 to 10%	2	-2	**3**
	Notebooks	1987	2	50 to 100%	4	0	**6**
	Netbooks	2007	4	10 to 50%	3	+2	**9**
	Nettops/Mini-PCs	2005	4	10 to 50%	3	+2	**9**
	Thin clients	1997	3	1 to 10%	2	-2	**3**
	LCD monitors	1989	2	50 to 100%	4	0	**6**

Product field		Market introduction in Germany	Value	Market share in 2011 (time of investigation)	Value	Rank in the product field	**Diffusion dynamics**
Energy efficiency in data centers	Energy-efficient servers	2005	4	10 to 50%	3	+2	**9**
	Server energy management	2003	4	10 to 50%	3	+2	**9**
	Solid-state drives	2006	4	1 to 10%	2	0	**6**
	Fiber optic cables	1983	2	10 to 50%	3	0	**5**
	Highly efficient uninterruptible power supplies	2002	4	50 to 100%	4	+2	**10**
	Water-cooled racks	2007	4	1 to 10%	2	0	**6**
	Hot aisle/cold aisle separation	2000	4	1 to 10%	2	-2	**4**
	Free cooling	1980	2	50 to 100%	4	0	**6**
	Blade servers	2001	4	10 to 50%	3	+2	**9**
	Server virtualization	1999	3	10 to 50%	3	0	**6**
Telecommunications and online media	E-mail	1993	3	50 to 100%	4	+2	**9**
	Teleconferencing	1993	3	10 to 50%	3	0	**6**
	Videoconferencing	1991	3	1 to 10%	2	-2	**3**
	Virtual answering machines	1997	3	1 to 10%	2	-2	**3**
	Teleworking	1989	2	10 to 50%	3	0	**5**
	MP3 music files	1995	3	10 to 50%	3	0	**6**
	Video on demand	2006	4	10 to 50%	3	+2	**9**
	Online marketplaces for second-hand goods	1999	3	10 to 50%	3	0	**6**
	Digital cameras	1991	3	50 to 100%	4	+2	**9**
	E-book readers	2008	4	0 to 1%	1	0	**5**
Sustainable mobility	Hybrid vehicles	1997	3	0 to 1%	1	0	**4**
	Electric cars	1995	3	0 to 1%	1	0	**4**
	3-liter (75 mpg) cars	1999	3	0 to 1%	1	0	**4**
	Natural gas cars	1995	3	0 to 1%	1	0	**4**
	Low-resistance tires	1992	3	1 to 10%	2	0	**4**
	Carsharing	1988	2	0 to 1%	1	-2	**1**
	Ride-sharing agencies	1968	1	0 to 1%	1	-2	**0**
	Mobile navigation devices enabling drivers to avoid traffic jams	2006	4	50 to 100%	4	+2	**10**
	German half-price railcard	1992	3	10 to 50%	3	+2	**8**
	Auto trains	1930	1	0 to 1%	1	-2	**0**

Case analysis. We prepared a qualitative profile for each case, using secondary information. This secondary information was available in the form of market analyses, life-cycle analyses, websites of inventors, manufacturers, wholesalers, and retailers as well as product- or use-related Internet sources. In total, about 5,000 sources of information were accessed and about 1,200 were cited in the 100 case studies. The description of the cases in each of the profiles followed a defined format and a given coding system (cf. Appendix 1). This included key data on the object of innovation and the diffusion process as well as the 22 variables (cf. Table 3) which we had elaborated as potentially relevant for the trajectory of the diffusion process. In this way, it was possible to survey qualitative secondary information quantitatively. At the same time, this en-sured that we surveyed the same data for all cases. In other words, the procedure is similar to participant observation.

The profile format fulfilled the function of a standardized survey instrument, similar to a standardized observation protocol. We surveyed the variables using 3-point scales (2, 1, 0 or 0, -1, -2) and 5-point scales (-2 to +2). The result of the survey was a dataset including key data about 100 cases of sustainable innovations as well as values for the 22 independent variables.

A coding team evaluated the independent variables using the 3-point and 5-point scales and assigned a value to each factor in each case. For example, we coded the case "heat pumps" with the value of 0 for the variable "perceptibility," since the innovation is hardly visible to the public and perceptibility can thus neither be assigned an effect promoting (+1 or +2) or inhibiting (-1 or -2) diffusion. The coding team comprised five researchers with specific expertise in the particular technology, product/service, or market.

We took two measures to ensure inter-rater reliability. First, we conducted a pretest in which all the researchers (observers) analyzed and coded the same case independently of one another. We specified details for assessing the cases in a uniform manner on this basis. Second, at least one person, usually two, checked and evaluated each of the 100 profiles again. The team of five researchers, who then jointly specified the evaluations, discussed any deviations. In this way, we quantified qualitative data in the present paper and made them accessible to statistical evaluation without claiming in the slightest to have depicted causal relationships or undertaken measurements. For this reason, we first carried out the quantitative evaluation descriptively with the goal of identifying groups of sustainable innovations that are comparable in terms of certain factors and their diffusion trajectories.

Factor analysis. We conducted a factor analysis to identify linkages between the independent variables. The goal of a factor analysis is to reduce the complexity of a dataset and potentially discover structures that may not have been surveyed but nonetheless exist empirically (Hair et al., 2006; Hardy & Bryman, 2004). A factor analysis produces new variables that indicate the linkage of each of the 22 empirical factors with the newly calculated factors in form of factor loading. In other words, the reduction of complexity is achieved by consolidating factors that "fit together," as it were, to form a single new factor. The first step in the factor analysis was to perform calculations to verify the suitability of the 22 factors for factor analysis. Here, the variable "institutional obstacles" (factor 16) proved mathematically unsuitable; we excluded it from the further analysis for this reason. We then calculated the principal component analysis with a varimax rotation (Hair et al., 2006; Hardy & Bryman, 2004). Compared with other methods of factor analysis, this method has the advantage of maximizing the factor loadings of those factors with especially high loads. This serves to support content-related interpretation of the newly determined factors and their later use in cluster analysis. We based the naming of the new factors on our interpretation and oriented it toward the 22 original variables and their loading on the factors.

Cluster analysis. In order to identify diffusion paths, it was necessary to elaborate groups of innovations that are as similar as possible with a view to the factors. In other words, we posited that some of the sustainable innovations studied here are similar concerning the factors we had identified in the factor analysis and that influence the diffusion process. To this end, we used the method of cluster analysis. In cluster analysis, cases are assigned to groups on the basis of influencing factors. They are assigned in such a way the homogeneity within a group is maximized while homogeneity between groups is minimized. In the present case, we conducted a cluster center analysis using the latent variables identified in the factor analysis (Hair et al., 2006; Hardy & Bryman, 2004).

4 Results

4.1 Correlation and results from the factor analysis

We tested the correlation between the 22 independent variables and the three dependent variables "market share," "diffusion time" and "diffusion dynamics" (cf. Table 3).

Table 3. Correlations between 22 independent variables and 3 dependent variables of 100 diffusion cases

		Dependent variables		
Factor group	Kendall's tau-b and approximate significance Independent variable	Market share	Duration of the diffusion process since market introduction	Diffusion dynamics
Product-related factors	Relative advantage of the innovation			
	Perceptibility			
	Compatibility			0.158*
	Low complexity			
	Trialability			
Adoptor-related factors	User innovators	-0.203*	-0.175*	-0.190*
	Low need for behavior modification	0.316**		0.235**
	Uncertainties on the part of adoptors	0.264**		0.292**
	Price, costs, cost-effectiveness	0.198*		0.160*
Supplier-related factors	"Green" pioneers	-0.207*		
	Renown and reputation of suppliers	0.326**		0.276**
	Completeness and availability of service	0.269**	0.201*	0.315**
Sector-related factors	Role of the industry trade association			
	Role of market leaders	0.235**	0.330**	0.385**
	Intermediaries as change agents			
Policy-related factors	Institutional obstacles			
	Governmental push and pull activities		-0.328**	-0.164*
	Lead market policies			
	Media and campaigns			
Path-related factors	Path dependencies			
	Price development	0.176*		
	Self-reinforcing effects	0.285**		

*Values of Kendall's tau-b: 0 to 0.05: no correlation; up to 0.2: weak correlation; up to 0.5: medium correlation; more than 0.5: strong correlation. Only those correlations that are at least significant and at least weak are shown. * significant at 5% level; ** significant at 1% level*

The fact that we could identify a significant correlation with regard to the key dependent variable "diffusion dynamics" for just 9 of the 22 factors suggests that further latent variables are hidden behind the surveyed variables. For this reason, we conducted a factor analysis (cf. Chapter 3.3) to clarify whether such latent variables that impact the diffusion trajectory exist. We carried out a principal component analysis with a varimax rotation (cf. Table 4). We drew mostly on the strong factor loadings (> 0,5 or < -0,5) for the substantive interpretation and characterization of the new factors. The factor analysis explains 62.9% of the variance, i.e., the seven newly developed factors can explain 62.9% of the variance in the field. According to Bartlett's test of sphericity, the analysis is highly significant ($p < 0.01$).

Table 4. Factor analysis: Rotated component matrix

Component	Market power of established suppliers	Political push & pull	Small Influence of pioneers	Incentive to buy	Compatibility with routines	Price and cost-effectiveness	Comprehensibility of the innovation
	1	2	3	4	5	6	7
Factor 1: Relative advantage of the innovation	-.095	.187	-.082	.687	.135	-.055	.273
Factor 2: Perceptibility of the innovation	.170	.017	.561	-.015	-.167	-.015	-.147
Factor 3: Compatibility of the innovation	-.106	-.139	.035	.113	.602	.272	.250
Factor 4: Complexity of the innovation	.064	-.078	-.002	.032	.004	.077	.831
Factor 5: Trialability of the innovation	.293	-.634	.297	.063	-.099	-.108	.085
Factor 6: User-innovators	-.167	-.180	.741	.173	-.032	.085	-.002
Factor 7: Need for behavior modification	.128	.060	-.168	-.031	.779	-.183	-.102
Factor 8: Uncertainties on the part of adoptors	.031	-.001	-.268	.112	.290	.082	.487
Factor 9: Price, costs, cost-effectiveness	-.030	.184	-.157	.019	-.013	.805	.312
Factor 10: "Green" pioneers	-.034	.180	.705	-.231	.249	-.258	.025
Factor 11: Size and reputation of suppliers	.730	.040	-.092	.236	.201	.099	.044
Factor 12: Completeness/availability of service	.467	-.092	.160	.134	.501	.122	.220
Factor 13: Role of the industry trade association	.354	.626	-.181	-.064	-.036	.156	-.154
Factor 14: Role of market leaders	.495	-.285	-.417	.196	.089	-.368	-.014
Factor 15: Intermediaries as change agents	.620	.280	.195	-.142	-.083	-.101	.369
Factor 17: Governmental push and pull	-.142	.744	.171	.164	.036	-.314	.141
Factor 18: Lead market policies	.069	.725	.197	.167	-.172	.119	-.014
Factor 19: Media and campaigns	.483	.193	.417	.209	-.210	.282	-.060
Factor 20: Path dependency	.552	-.264	-.056	-.269	-.003	-.011	-.133
Factor 21: Price development	.149	.003	.057	.812	-.008	.124	-.100
Factor 22: Self-reinforcing effects	.306	-.227	.168	.250	.226	.564	-.300

Values of the factor loadings: > 0.5 and < -0.5: strong loading; 0.4 to 0.5 and -0.4 to -0.5: weak loading

The principal component analysis with a varimax rotation revealed seven new factors. The derivation of the seven new factors can be explained as follows:

Factor 1: Market power of established suppliers. The variables “size and market power of suppliers,” “intermediaries as change agents,” and “path dependency” load highly on the factor. The variables “role of market leaders,” “media and campaigns,” and “completeness and availability of products and services on the market” round out the picture with weak loadings. Overall, a factor emerges that encompasses both the suppliers themselves and the market and policy intermediaries active in their environment. The new factor is therefore most aptly described as “market power of established suppliers.” The high loading of the variables “size and reputation of suppliers” as well as the high loading of the factor “path dependency” imply the existence of a factor that would tend to describe the diffusion of incremental innovations of existing and established products that have already formed their paths. The factor explains 11.3% of the variance of the 22 original factors.

Factor 2: Political push & pull. “Governmental push and pull activities” and “lead market policies” load highly on the factor, the “role of the industry trade association” loads weakly. If the role of an industry trade association in relation to the prevalence and support of an innovation is considered mainly as political lobbying, then the new factor can be most precisely described by the term “political push & pull.” The factor is the only one that describes the effect of governmental support instruments on the diffusion of innovations. The factor explains 11.25% of the variance of the 22 original factors.

Factor 3: Small influence of pioneers. What is remarkable about this factor is that both the variables “user-innovators” and “green pioneers” load similarly, even though the user-innovators take on a pioneering role on the demand side, while the “green” pioneers are on the supply side. This shows that the influence of the two sides – suppliers and adoptors – should not be considered separately, but can certainly be combined in a single aggregate factor. This factor is described most accurately as “small influence of pioneers”, since user innovators and small green pioneers usually have significantly less resources and power to influence market penetration than established market leaders and big companies. The factor also refers to possible cooperation between pioneering “green” suppliers and user-innovators, who are supported by strong “perceptibility of the innovation” as well as a presence in “media and campaigns.” The fact that the role of market leaders loads slightly negatively points to the fact that they often are not among the first to supply an innovation. For this reason, one may assume that there is often a division of labor, as it were, between pioneering suppliers and market leaders. While it is mostly newly established and small companies that take on the role of pioneering suppliers in the case of radical innovations, the established companies are more strongly represented in the case of incremental innovations. In the case of radical innovations, market leaders often appear to enter into the market as followers only at a later point in time. The factor “small influence of pioneers” explains 10.17% of the variance of the 22 original factors.

Factor 4: Incentive to buy. The variable “price development” loads very highly on the factor, the variable “relative advantage of the innovation” somewhat less highly. The factor refers to the high incentive to buy that is triggered by significant price reductions. The fact that the factor “relative advantage” also loads highly suggests that besides a good price, adoptors must perceive both a useful function and an advantage in order to make the decision to buy. The new factor is therefore most aptly described as "incentive to buy." The factor explains 7.7% of the variance of the 22 original factors.

Factor 5: Compatibility with routines. The adoptor-related variable "need for behavior modification," the product-related variable "compatibility," and the supplier-related variable "completeness and availability of service" load highly on the factor, whereby "need for behavior change" loads most highly by far. All three original variables refer to "compatibility with routines," which is why this is an appropriate term for the new factor. It suggests that the adoptors are in principle change-averse in terms of both purchasing and use and that it is safe to assume that an innovation's ability to prevail as well as its diffusion dynamics depend decisively on its compatibility with routines during purchase and use. The factor explains 7.65% of the variance of the 22 original factors.

Factor 6: Price and cost-effectiveness. The variable "price, cost, cost-effectiveness" loads highly on the factor, the variable "self-reinforcing effects" does so somewhat less. In contrast to the factor "incentive to buy" (see above), this is about the price difference between the innovation and (established) competing products or about the cost-effectiveness of innovative durable consumer goods or investment goods. High cost-effectiveness seems to result in self-reinforcing effects which obviously also have an effect in the case of this factor. The new factor is to be called "price and cost-effectiveness." It explains 7.5% of the variance of the 22 original factors.

Factor 7: Comprehensibility of the innovation. The product-related variable "complexity of the innovation" loads highly on this factor, the adoptor-related variable "uncertainties on the part of adoptors" significantly less highly. If the comprehensibility of a product increases, i.e., if its complexity is reduced, this apparently diminishes uncertainties on the part of adoptors. That is why the new factor will be called "comprehensibility of the innovation." It explains 7.4% of the variance of the 22 original factors.

The analyses show that the original classification of the 22 factors in product-, adoptor-, supplier-, sector-, policy, and path-related factors for descriptive purposes does not readily result in the identification of individual factors as primary drivers of the diffusion process. Instead, the seven newly identified factors make clear that influences from several "spheres of influence" (product, adoptor, supplier, sector, policy, path) interact and have joint impacts. The new factors then had to be tested for their significant effects on the dependent variables and their sustainability effects. Since the newly formed factors are metric variables, we calculated the Pearson coefficient of correlation.

Various correlations between the seven new factors and the dependent variables exist. In our sample, the factor "market power of established suppliers" correlates most strongly with the dependent variables. This is true of the market share, the speed of diffusion, and the indicator for diffusion dynamics.

Table 5. Correlation between 7 independent variables and 3 dependent variables of 100 diffusion cases

	Pearson coefficient of correlation		
Factor	**Market share** (Kendall's tau-b)	**Duration of the diffusion** (Kendall's tau-b)	**Diffusion dynamics** (Pearson)
Market power of established suppliers	0,240**	0,209**	0,321**
Political push & pull		-0,144*	
Small influence of pioneers	-0,217**	-0,193**	-0,294**
Incentive to buy			
Compatibility with routines	0,190*		0,255*
Price and cost-effectiveness	0,156*		
Comprehensibility of the innovations			

**The correlation is significant at the 0.05 level (2-tailed). **The correlation is significant at the 0.01 level (2-tailed).*

For the factor "political push & pull," we could not determine any significant correlations with the indicators market share and diffusion dynamics. Possible reasons include that government interventions and political lobbying on the part of trade associations are not equally relevant across all diffusion cases, but differ according to product field and type of diffusion. In other words, this could be an indication that it is important to differentiate between different kinds of innovations and diffusion paths.

The fact that the factor "small influence of pioneers" correlates negatively with the dependent variables can be explained by the fact – as is also the case with the individual original factors – that many innovations introduced to the market by "green" pioneers are (1) marketed by lesser-known firms, so they cannot benefit from the advantages of a well-known brand or company in terms of brand awareness and trust, and (2) that far fewer resources are available for marketing and distributing these innovations because they are often supplied by small businesses. User-innovators are also typically individuals who may vigorously advocate an innovation because they expect concrete advantages from using it, but generally have a small amount of resources to promote the prevalence and availability of the innovation. In addition, it is important that the share of the radical innovations introduced to the market by "green" pioneers is higher, which explains longer diffusion times. For at the 1% level (p = 0.002), there is a significant correlation of medium strength (tau-b = 0.276) between the characteristic "radical innovation or incremental innovation" and the diffusion time, which is longer for radical innovations.

The factors "incentive to buy" and "comprehensibility of the innovation" do not display any correlations with the dependent variables in the sample studied. Here, too, this may be caused by the fact that the price development of innovative products and their relative advantage as well as the comprehensibility of a new product or service on the market may not be equally important across all product groups and diffusion cases. This could be an indication that it is important to differentiate between different kinds of innovations and diffusion paths.

"Compatibility with routines" displays a significant correlation both for market share and for the indicator "diffusion dynamics." Thus, the factor appears to be of substantial importance for the trajectory of the diffusion process across all 100 diffusion cases studied. The results also suggest that compatibility with routines is very strong specifically in the case of the incremental innovations offered by market leaders and that this has positive effects on market share and diffusion dynamics.

"Purchase price and cost-effectiveness" display a weakly significant correlation with market share. The dependent variable "diffusion dynamics" is more important, however. Here, we could not ascertain a significant correlation in the sample studied. In this case, too, the reason might be that the factor is not equally important across all product groups and diffusion cases. So this could also be an indication that it is important to differentiate between different kinds of innovations and diffusion paths.

4.2 Results from the cluster analysis

As the calculations of the correlations and the factor analysis have shown, it is possible only to a limited extent to identify factors significant across all diffusion cases. For this reason, it made sense to examine whether certain groups of diffusion processes could be identified within the totality of all diffusion cases. In order to identify diffusion paths, it was necessary to elaborate groups of innovations that are as similar as possible with a view to the factors. The cluster analysis (cf. 3.3.6) yielded five clusters shown in Table 6.

Table 6. Cluster centers

	Cluster				
	Efficiency-enhancing investment goods from established suppliers	Comprehensible products for end users	Government-supported investment goods from pioneering suppliers	Radical innovations requiring major behavior modifications	Complex products with unclear or long-term benefits
	1	2	3	4	5
Market power of established suppliers	.99160	.34578	-.47389	-.64769	-.80748
Political push & pull	-.32205	-.32389	.86447	-.00058	.14153
Small influence of pioneers	-.55480	-.10547	.61458	.31545	-.37331
Incentive to buy	-1.11651	.31417	.02196	-.14456	.08638
Compatibility with routines	-.05103	.26034	.83118	-1.86155	-.20292
Price and cost-effectiveness	.72731	-.36589	.65029	.56147	-1.02361
Comprehensibility of the innovation	-.38440	.36159	.05332	.47251	-1.53775

The five clusters identified can be described by the key characteristics, actors, and strength of diffusion dynamics shown in Table 7.

Table 7. Characterization of clusters of diffusion of sustainable innovation

Cluster	Key characteristics	Actors	Diffusion dynamics	Examples
Efficiency-enhancing investment goods from established suppliers	High cost-effectiveness due to increased efficiency Predominantly investment goods Predominantly incremental innovations Minor functional benefit Require few behavior modifications Government support does not play an important role	Predominantly established suppliers with good reputations	High	Highly efficient uninterruptible power supply (UPS) Energy-efficient servers Videoconferencing services
Comprehensible products for end users	Good comprehensibility of the innovation Almost exclusively goods for end users Predominantly well-known products with improved characteristics Good trialability Require few behavior modifications	Predominantly established suppliers with good reputations	High	Organic milk Highly efficient dish-washer MP3 music file
Government-supported investment goods from "green" pioneering suppliers	Strong political push & pull Almost exclusively investment goods Good technical compatibility Few behavior modifications on the part of purchasers Cost-effectiveness (because of government support)	High significance of "green" pioneers and the government	Medium	Photovoltaics Passive houses Wind power plants
Radical innovations requiring major behavior modifications	Strong need for behavior modifications on the part of users Predominantly high degree of innovation Obstacles because of strong path dependence Good comprehensibility of the innovation No self-reinforcing effects yet in spite of government support	High significance of start-ups and young businesses	Low to medium	Thin client & server-based computing Bioenergy villages Carsharing
Complex products with unclear or long-term benefits	Complex products or systems High purchase price or unclear cost-effectiveness Low capacity for connection to existing technical system requires change of system Weak political push & pull	Predominantly small businesses with scant reputation	Low	Long-term thermal energy storage Absorption refrigeration systems 3-liter (75 mpg) cars

5 Conclusions

5.1 Key insights

In order to clarify the question “What are key factors influencing diffusion dynamics of sustainable innovation?”, we tested the correlation between 22 independent variables and three dependent variables: “market share,” “diffusion time,” and “diffusion dynamics.” The fact that we could identify a significant correlation with regard to the key dependent variable “diffusion dynamics” for just 9 of the 22 factors suggests that further latent variables are hidden behind the surveyed variables. For this reason, we conducted a factor analysis, which enabled us to identify seven new factors. Three of these new factors proved to correlate significantly with the diffusion dynamics of all 100 sustainable innovations investigated. The “market power of established suppliers” and the “compatibility with routines” correlate positively with diffusion dynamics and the “small influence of pioneers” negatively.

As the calculations of the correlations and the factor analysis have shown, it is possible only to a limited extent to identify key factors significant across all diffusion cases. For this reason, it made sense to examine whether certain groups of diffusion processes could be identified within the totality of all diffusion cases. The cluster analysis showed that five groups of sustainable innovations differ significantly in terms of the factors influencing the diffusion process and in terms of diffusion dynamics. The empirical investigation of 100 sustainable product and service innovations thus revealed that diffusion processes of sustainable innovations differ substantially and in which regard. This answers our second research questions “To what extent do diffusion processes of sustainable innovation differ from each other, and can different groups of diffusion processes be identified?” The characterization of clusters of diffusion of sustainable innovation allows for insights which factors, actors, and institutional settings are characteristic of different groups of diffusion processes, which clarifies our third research question.

5.2 Limitations

Since no large-scale study across sectors or product fields on the diffusion of sustainable innovations has been conducted to date, this study broke new ground for empirical research. As a pioneering empirical investigation in a very young field of research, the study naturally had to limit its scope. The results can claim validity only for sustainable product and service innovations and not for other types of innovations such as process, institutional, or social innovations. Furthermore it should be underlined that the investigation was limited to diffusion processes in one specific country (Germany). Despite the fact that this is one of the first large-scale studies on the diffusion of sustainable product and service innovations, the number of 100 cases is still limited when it comes to applying techniques of inductive statistics. In our sample we had 83 product innovations, but only 13 service innovations and 4 mixed product-service innovations.

5.3 Managerial implications

We identified three factors that correlate significantly with diffusion dynamics. This finding is particularly relevant for innovation management and new venture creation: (1) "Market power of established suppliers" correlates positively and the "small influence of pioneers" negatively with diffusion dynamics. Start-ups often underestimate the power and relevance of established companies and market players. If a new venture follows a strategy of fast growth, it should thoroughly check market forces and consider strategic alliances with established companies. (2) "Compatibility with routines" correlates positively with diffusion dynamics. This finding underlines the urgent necessity to assess the impact of a new product or service on user behavior in a very early stage of product development and to check the compatibility with routines systematically in the testing phase. Innovation management literature provides a broad array of methodologies and tools for user integration in idea and product development as well as in product testing. Innovation managers and decision makers should take this aspect of compatibility with routines very seriously when deciding on market introduction and developing marketing strategies.

The three factors which we identified as especially relevant for the diffusion success of sustainable product and service innovations as well as the differences between the five clusters of diffusion cases also have important implications for policy makers: (1) Our findings point out that some types of sustainable product innovations require substantial governmental support in order to diffuse. While the group of "Government-supported investment goods from green pioneering suppliers" (photovoltaics, wind energy etc.) is already well supported in Germany, policy makers and governmental organizations should thoroughly check the group of "Complex products with unclear or long-term benefits" as to their need for additional governmental intervention. (2) The fact that "compatibility with routines" correlates positively with diffusion dynamics leads to the recommendation that governmental R&D funding programs should consider this aspect more explicitly. This can, for example, be done by making it a requirement to assess this aspect in government-funded R&D projects and by providing a higher funding rate for radical innovations which require major changes in user behavior or organizational routines.

5.4 Further research

As the seven factors developed in the factor analysis demonstrate, what matters in the development of intervention strategies is precisely the interplay of the various fields of intervention and the simultaneous design of the factors. It is therefore the task of further analysis and research to develop a multi-intervention approach for influencing the diffusion of sustainable innovations. The evolutionary concept of diffusion paths presented in this article develops significant explanatory power on the basis of which faster or slower diffusion and the success or failure of sustainable innovations can be better understood. The next step in research on diffusion paths of sustainable innovation is to connect the insights on the factors, actors, and institutional settings which are characteristic of different groups of diffusion processes with the examination of key events (tipping points) in the trajectory of these processes.

The limits of our investigation outlined above indicate further research needs. One important question, for example, is whether there are significant differences between the diffusion processes of innovative sustainable products and innovative sustainable services. Answering this kind of questions will permit the development of diffusion paths of sustainable innovation and will offer concrete starting points for interventions by policy-makers, innovation actors, and societal groups.

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Appendix 1: Profile and coding system for diffusion cases

Table 8. Case profile

Description of the diffusion case

Object:

What exactly is the object of innovation?

What about it is new?

How can the innovation be differentiated from previous/other products/services/solutions?

Is this a product [ ], a service [ ], or a combination of the two [ ]?

Market introduction:

When was the innovation introduced to the market in Germany?

Was it introduced to the market by established suppliers [ ], new companies[1] [ ], or both [ ]?

Adoptors:

Who are the adoptors?

End users (households) [ ], professional users (businesses, public sector, etc.) [ ]?

End users: Is this a product/service purchased routinely (i.e., purchased more than once per year) [ ] or not [ ]?

Professional users: Is this a capital good (depreciable) [ ] or a consumable [ ]?

Sector

The innovation is in which sector?

Description: NACE code: [2]

When was the industry or trade association in Germany established? ______

Key events

Which events had major effects on the diffusion trajectory to date, and which ones are responsible for bifurcation and multifurcation points or for linkages between paths?

Squeeze out

Is the innovation on the market at the same time as its predecessor product, or is only one or the other on the market?

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[1] A "new company" is defined here as a company that was established for the purpose of developing and marketing the innovation in question.

[2] Nomenclature statistique des activités économiques dans la Communauté européenne (NACE) is the Statistical Classification of Economic Activities in the European Community.

Both at the same time [ ], one or the other [ ]

Basic innovation

Is this a basic innovation or an incremental innovation?

Basic innovation [ ], incremental innovation [ ]

Data collection about the individual diffusion cases and coding of the values of the individual factors followed the format described above.

For each diffusion case, exactly one value was assigned to each factor. We gathered the information required for this coding from documents available online and offline and documented the sources in an appendix. We studied a total of approx. 5,000 sources, most of them on the Internet, and cited approx. 1,200. In order to ensure intersubjective reproducibility and inter-rater reliability, a coding team composed of several people coded the case profiles, and team members reviewed each other's work.

As a matter of principle, the coding referred to the entire diffusion process to date, i.e., to the period from market introduction to today, using the information available. Where differentiation according to various phases was necessary, we noted this explicitly.

Coding followed the principle of rejecting the null hypothesis. In general, we assumed each factor to have zero influence. Only in cases where the empirical information suggested a different assumption in a manner that was indisputable and intersubjectively transparent did we assign a value of 1 or 2 for a supporting or very strongly supporting influence or -1 or -2 for an inhibiting or very strongly inhibiting influence.

Table 9. Code system for the assessment of factors in diffusion cases

Product-related factors	Code
1. Relative advantage of the innovation: Which functional or economic advantage does the innovation have in comparison with the predecessor product?	2: New useful function or strong cost advantage 1: Less important new function or small cost advantage 0: No relative advantage discernible
2. Perceptibility: In the absence of particular efforts to provide information about the innovation, can third parties perceive its use?	2: Clearly perceptible AND perceptible in public 1: Less clearly perceptible or perceptible only in interior spaces or the like 0: Not perceptible
3. Compatibility: Does the innovation have the capacity for connection to the existing technical, institutional, and cultural systems?	2: The innovation can easily be connected and has synergies with its environment 1: The innovation can easily be connected and results in small advantages in its environment 0: Neutral -1: Connection requires time and effort or learning -2: Capacity for connection can be established only with difficulty
4. Complexity: Is the innovation complex for the adoptor, and is specialized knowledge required to understand it?	0: Uncomplex -1: Slightly complex -2: Requires specialized knowledge
5. Trialability: Can users try out the innovation without much time and effort?	2: Easy to try out and at low cost 1: Trying out the innovation requires considerable time and effort 0: Cannot be tried out

Adoptor-related factors	Code
6. User innovators: Can user innovators be identified during the *innovation process* or at the time of market introduction? If so, who are they, and what kind of innovators are they? Are there indications that user innovators were integrated in the manu-	2: A larger group of innovators exists 1: A smaller group of innovators exists 0: Unknown

facturer's innovation process in a targeted fashion?	
7. Need for behavior modification: Does use of the innovation require behavior modification on the part of the adoptor?	0: No behavior modification required -1: Behavior modification required -2: Significant behavior modification required
8. Uncertainties on the part of adoptors: To what extent were or are there uncertainties on the part of the adoptors concerning the innovation?	0: No uncertainties known -1: Minor uncertainties -2: Significant uncertainties
9. Price, costs, cost-effectiveness: To what extent do aspects relating to price, costs, or cost-effectiveness support or inhibit adoption of the innovation?	2: High cost-effectiveness or cheaper 1: Lower cost-effectiveness or somewhat cheaper 0: Neutral -1: Slightly uneconomical or somewhat more expensive -2: Significantly uneconomical or significantly more expensive

Supplier-related factors	**Code**
10. "Green" pioneers: Do pioneering suppliers of the innovation have ecological goals and convictions?	2: The innovation was/is supplied by pioneers with explicitly "green" or sustainable goals 1: "Green" or sustainable goals played a (minor) role 0: No "green" goals on the part of the pioneering suppliers
11. Renown and reputation of the suppliers: Do suppliers of the innovation who are well-known and have a good reputation exist already?	2: Well-known companies with a good reputation supply the innovation 1: Less well-known companies supply the innovation 0: Only suppliers who are not well-known
12. Completeness and availability of service: Is the innovation offered for sale on the market with a complete service package, and is it easily available to customers?	2: Availability and service are guaranteed everywhere 1: Minor limitations to availability or service 0: Neutral -1: Poor availability or lacking service have slightly inhibiting effects -2: Poor availability or lacking service have distinctly inhibiting effects

Sector-related factors	Code
13. Role of the industry trade association: Is an industry trade association in existence at the time of market introduction; does it have political influence, and does it use it for supporting the innovation?	2: Strong and active industry trade association 1: Less strong or less active industry trade association 0: No industry trade association
14. Role of market leaders: Who were the market leaders in the industry in which the innovation was introduced, and do they support or inhibit its diffusion?	2: Market leaders were involved in introducing the innovation from the beginning 1: Market leaders provided slight support for the innovation 0: Market leaders remained neutral -1: Market leaders slightly inhibited the diffusion -2: Market leaders steadfastly opposed the diffusion
15. Intermediaries as change agents: To what extent have market intermediaries (e.g., wholesalers and retailers) and policy intermediaries (e.g., energy, efficiency, climate protection agencies) accelerated or inhibited the diffusion trajectory to date?	2: Numerous intermediaries steadfastly supported the diffusion 1: Some intermediaries supported the diffusion 0: No active intermediaries known

Political factors	Code
16. Institutional obstacles: To what extent have legal or administrative rules inhibited the diffusion of the innovation to date?	0: No obstacles -1: Minor obstacles -2: Significant obstacles
17. Governmental push and pull activities: To what extent was the diffusion of the innovation accelerated by regional, national, or EU-wide provisions (push) or support activities (pull)? Did explicit environmental or sustainability goals play a role?	2: Significant support 1: Limited support 0: No support
18. Lead market policies: Is the innovation part of a targeted lead market policy at the regional, national, or EU level? Do explicit environmental or sustainability goals	2: A lead market policy is being pursued actively 1: Minor aspect of a lead market 0: Unknown

play a role?

19. Media and campaigns: To what extent did the media (press, radio, TV, etc.) and NGO campaigns accelerate or inhibit the diffusion trajectory?	2: The innovation was a topic in the media for a longer period of time 1: The innovation has been a topic in the media sporadically 0: Reporting about the innovation is rare

Path-related factors	**Code**
20. Path dependencies: To what extent have technological or economic path dependencies inhibited the speed of diffusion to date?	2: The innovation developed very rapidly to become the dominant design 1: The innovation has achieved the status of dominant design in some market segments 0: Neutral -1: Predecessor products inhibited diffusion because of minor lock-in effects -2: Predecessor products inhibited diffusion because of major lock-in effects
21. Price development: How has the price (adjusted for inflation) developed over the course of the diffusion process?	2: The price has decreased significantly since market introduction, for example through economies of scale or subsequent innovations 1: The price has decreased slightly 0: The price has remained constant or has increased
22. Self-reinforcing effects: Can self-reinforcing effects, e.g., imitation of role models/celebrities/opinion leaders or critical mass phenomena be observed?	2: Significant critical mass phenomenon 1: Slight critical mass phenomenon 0: No self-reinforcing effects

Data collection about the effects of the diffusion followed the format documented below.

Table 10. Code system for the assessment of factors in diffusion cases

Categories of effects	Code
Effects at the product level: Does the individual product have a proven beneficial social or ecological effect? Are facts and figures available in this regard?	2: Significant improvement compared with the predecessor product 1: Slight improvement 0: No improvement known
Rebound effects: Are rebound effects to be observed, or are they likely to occur in the future?	0: No rebound effects known or to be expected -1: Rebound effects very likely to be expected -2: Significant rebound effects are already proven or obvious
Ability for re-invention: Does the innovation provide the opportunity for regional or user-specific modifications and inventions? Does the innovation provide a basis for subsequent innovations?	2: This is a basic innovation that obviously creates many new opportunities 1: Individual modifications or subsequent innovations are known 0: Unknown
Diffusion curve: Which data about the diffusion have become known over time, and how large is the market share of the innovation in Germany today?	Uncoded: Documentation of development of market share over the longest possible period of time, depending on data availability
Market penetration: What is the market share of the innovation on the accessible market at this point in time?	4: 50 to 100% 3: 10 to 50% 2: 1 to 10% 1: 0 to 1%