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Functions of Innovation Systems: the Case of Flywheel Energy Storage

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Abstract: Transitions from conventional to more sustainable systems, such as in the case of energy transitions, depend on new technological developments and social change processes. To understand how the formation and growth of more sustainable technologies work, we apply the theory of technology innovation systems (TIS) and functions of innovation systems (FIS) to the flywheel energy storage technology. Flywheels are rotating masses allowing energy storage in kinetic form and can be a green alternative to chemical-laden batteries, amongst others. Using a qualitative embedded case-study with multiple units of analysis in German-speaking countries, our research reveals a mitigated situation, several malfunctioning processes and negative causal dynamics. Central is the lack in consistency in the direction of search, important legitimacy issues, strong market segmentation and unfavorable market support mechanisms that lead to low resource availability, together preventing the TIS to grow from isolated experiments to niche markets.

Keywords: Technological Innovation System; Technology management; Renewable Energy; Radical innovation; Green innovation

1 Introduction

Transitions from conventional to more sustainable systems, such as in the case of energy transitions, depend – next to new social practices – mainly on new technological developments in areas such as renewable energy technology, energy storage technology, and efficiency technologies. It is assumed that the transition from one dominant large-scale socio-technological system to another is a complex process that unfolds over time and is influenced by the interaction of a multitude of social, political and technological factors.

While others focus on the meta-level process of transition (e.g. transition management, Rotmans *et al.*, 2001; the multi-level perspective, Geels, 2002), we are more interested in specific innovation systems as part of those transitions. This can be captured with technological innovation systems (TIS) approach (Edquist, 1997; Carlsson *et al.*, 2002; Markard and Truffer, 2008), which emerged with the desire to manage the direction of technology development. Its primary aim is to inform decision-makers on possible leverages to manage and control the direction in which they evolve.

The literature suggests that a systems approach can support informed decision-making about technological transitions (Edquist, 1997). However, knowledge on the formation and growth of TIS is still at an early stage (Bergek *et al.*, 2008; Jacobsson *et al.*, 2004). Assuming that a number of functions need to be fulfilled for the growth and maturation of a TIS, the functions in innovation systems (FIS) framework focuses on key functions or processes within the TIS (Hekkert *et al.*, 2007; Bergek *et al.*, 2008). However, more empirical work is needed to understand the underlying processes and to identify key challenges for policy makers and possible strategies for entrepreneurs (Bergek *et al.*, 2008).

While several cases of TIS in the domain of energy *generation* are discussed in literature (Kamp, 2008; Negro and Hekkert, 2008; van Alphen *et al.*, 2008), energy *storage* technologies have not been considered. Energy storage is necessary in energy transitions, as grid integration poses increasing stability issues when intermittent renewable energy generation strongly increases (Akinyele and Rayudu, 2014). The flywheel technology is a promising storage option that is based on a mass rotating at various speeds allowing energy storage in kinetic form. In this context, this paper discusses the formation of the flywheel energy storage innovation system in Germany.

This paper aims to evaluate the stage of development and the performance of the flywheel TIS using the FIS framework. Our research investigates both the structure (i.e. actors, networks and institutions) and dynamics (i.e. functions) of the TIS. The paper features a qualitative embedded case study with multiple units of analysis.

The findings reveal a mitigated situation in the flywheel TIS. Whereas the structural analysis showed a well formed system, several malfunctioning processes limit its potential for growth. These processes reveal negative dynamics, including low resource availability that prevents markets to form. Indeed, the lack of resources is pervasive in the system and can be explained as the result of a cumulative negative causation of lacking consistency in the direction of search, important legitimacy issues, strong market segmentation and unfavorable market support mechanisms. Consequently, little resources are available for building pilot project that could increase legitimacy and attract investors who could, in turn, fund projects and enable market development.

The main contribution to the literature is an in-depth empirical case study that allows for further refinement of the FIS framework (Bergek *et al.*, 2008). Second, by translating the outcomes of the FIS analysis in terms of market opportunities, we illustrate how the FIS framework can be of relevance to entrepreneurs, a topic which was only recently addressed in the literature (Pohl and Yarime, 2012). Third, related to the empirical context, we expand extant TIS studies from energy *generation* to the emerging field of energy *storage*.

2 Literature review

2.1 Technology innovation systems and functions of innovation systems

TIS theory emerged with the desire to manage the direction of technology development and its primary aim is to inform decision-makers on the leverages to manage and control the direction in which it evolves. The literature suggests that informed decision-making about technological transitions can be supported with a systems approach (Carlsson *et al.*, 2002; Bergek *et al.*, 2008). However, knowledge on the formation and growth of TIS is still at an early stage (Bergek *et al.*, 2008; Jacobsson *et al.*, 2004). Central in the analysis of a TIS are three structural elements: actors, networks and institutions (Carlsson *et al.*, 2002). In the literature, innovation system failures are discussed as perceived weaknesses in the structure of the system. Institutional, network or capability failures are typically discussed.

It is difficult to assess the 'goodness' or 'badness' of structural elements without referring to their context, the effect on other structural elements and the overall system. Therefore, some scholars adopt a functional approach and claim that a process focus needs to complement the structural analysis (Bergek *et al.*, 2008). Assuming that a number of functions need to be fulfilled for growth and maturation of a TIS, scholars have proposed various sets of key functions (Chaminade and Edquist, 2005; Hekkert *et al.*, 2007; Bergek *et al.*, 2008). We follow the approach by Bergek *et al.* (2008) because it explicitly addresses positive externalities, which are relevant for sustainability-related innovations. The seven functions proposed are described in Table 1. Each function represents a process that the TIS needs to fulfill. These processes influence each other and can form positive and negative feedback loops. The analysis of the structure and the functions of a TIS allows to evaluate the driving and hindering development factors.

Table 1 Functions in the innovation system

No.	*Name*	*Description*
1	Knowledge development and diffusion	Knowledge development and diffusion related with the breadth and depth of the knowledge that is developed and how well it is diffused and combined in the system.
2	Influence on the direction of search	This functions analyses the incentives and/or pressures for organizations to enter the innovation systems. The quality of the direction of search determines the perceived entrepreneurial opportunities.
3	Entrepreneurial experimentation	This function focuses on how the potential of new knowledge, networks and markets are turned into concrete entrepreneurial activities (experiments) to generate, realize and take advantage of new opportunities.
4	Market formation	This function involves the identification of markets in which the new technology is valued.
5	Resource mobilization	This function focuses on the extent to which the TIS is able to mobilize human and financial capital as well as complementary assets.
6	Legitimation	Legitimacy is a prerequisite for the formation of new industries and by extension of new TIS.
7	Development of positive externalities	Outcomes that investors cannot fully appropriate but can be captured by the other societal actors and thus support the acceptance and desirability of the innovation in the general public.

Source: based on Bergek *et al.* (2008)

The extant literature features several cases studies of TIS in formation and growth. For instance the German solar cell (Jacobsson *et al.*, 2004), the Dutch biomass digestion (Negro *et al.*, 2007) and gas as alternative automobile fuel (Suurs *et al.*, 2010). However, more empirical research is needed to refine the FIS framework to inform the design of policy interventions (Bergek *et al.*, 2008) and entrepreneurial strategy making (Pohl and Yarime, 2012).

2.2 Flywheel energy storage technology

Energy storage has recently come in the foreground of the discussions in the context of energy transitions (Akinyele and Rayudu, 2014). Energy storage technologies are discussed as central components for the expansion of renewable energy generation and distribution in electricity grids. Indeed, past a certain level, storage of intermittent renewable energy sources is required to assure continuity of electricity supply. Another application is electric mobility (using renewable energy), in which mobile energy storage is needed for (hybrid) electric vehicles in order to enable grid-based charging or break energy recovery. Energy storage can therefore be seen to contribute to energy transitions in various contexts.

Whereas conventional batteries dominate the discourse on energy storage, many promising emerging technologies are often neglected, including technologies such as compressed air or thermal storage (Mahlia *et al.*, 2014). Another is flywheel technology, an energy storage based on a rotor spinning at various speeds allowing energy storage in kinetic form.

Flywheels can be considered as environmentally-friendly alternatives to conventional storage technologies, particularly chemical-based batteries (Liu and Jiang, 2007; Doucette and McCulloch, 2011; Mahlia *et al.*, 2014; Akinyele and Rayudu, 2014). Several different construction types are being developed (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

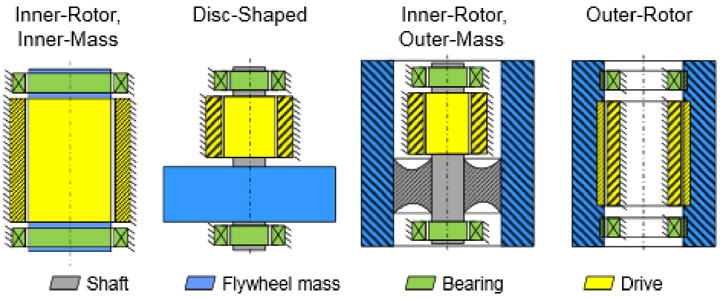

Figure 1 Overview of the different flywheel typologies (Schaede *et al.*, 2015)

Depending on the application, flywheels can compete against technologies such as batteries and super-capacitors and even offer slightly cost saving potentials (Doucette and McCulloch 2010). Compared to batteries, flywheels typically store less energy (Wh) but have a higher power output (W), even though the performance of batteries has strongly increased. However, flywheels store power only over a short period of time (12 hours at best). On the other hand, they have a very long service life that exceeds one million cycles, whereas batteries need replacement after 5-10 thousand cycles (Mahlia *et al.*, 2014). Further, unlike batteries, flywheel are made of non-toxic materials. Finally, considering their material composition, their manufacturing cost could become very low, when mass production and related economies of scale are achieved. With regard to super-capacitors, flywheel have a longer service life, can store more energy, and weigh less.

Flywheels, as ultra-short high power output storage devices, find various (potential) applications with two broad areas being most relevant: first in the electricity grid, where they can be used to store power excesses and thereby flatten out grid fluctuations. Second, off-grid, as an energy storage device. The most promising application seems to be to recover breaking energy vehicles that slows-down (see below).

3 Research method and case study

3.1 Research method

This research aims to evaluate the stage of development and the performance of the flywheel TIS. Our research investigates both the structure (i.e. actors, networks, institutions) and the dynamics (i.e. functions) of the flywheel TIS in Germany. According to (Yin, 2014), single case studies are adapted for research that require an in-depth examination of a contemporary topic and for theoretical domains which are still in an early stage. Other authors including Jacobsson *et al.* (2004), van Alphen *et al.* (2008) and (Pohl and Yarime, 2012) also followed this approach demonstrating the emerging character of the research field.

3.2 Case selection

The research presents a qualitative embedded case study with multiple units of analysis covering both individual economic actors and industry network-level entities and activities (Yin, 2014) of a TIS in the formative stage that is centered on the flywheel technology. The geographical focus is on Germany, but also covers neighboring (partly German speaking) countries contributing to the innovation system. The case has been chosen according to theoretical sampling (Eisenhardt, 1989) for being revelatory and representative (Yin, 2014).

The case is *representative* for the development of energy technologies that are not considered as “mainstream” solutions in the energy transition, as it investigates typical obstacles of theoretically promising technologies that do not receive sufficient support because they are not in the spot light of public discussions.

The case is also *revelatory* (Yin, 2014) because the researchers have an in-depth, intimate access to the actors of the TIS and were therefore able to derive rich data about the underlying processes, the innovation dynamics, the possible applications for the technology and their market potential. Following the philosophy of engaged scholarship (Van de Ven, A., 2007), the access was partly provided by trust-building measures in the industry. Indeed the authors organized an international workshop on the market opportunities of flywheels in the context of the German energy transition targeting scientists, industry experts, technology developers, system builders and end-users.

3.3 Data collection and analysis

The research relies on in-depth qualitative data. A strategy of triangulation based on data from various sources has been pursued, (i) 13 semi-structured interviews with important actors of the TIS, (ii) participatory-observation of a major industry event at the institute of the authors and more than 15 informal telephone interviews with participants, (iii) various internal meetings with selected actors involved in the system, (iv) ethnographic observation at various industry conferences and events and (v) archival analysis of industry-related documents. Finally, the data collection was complemented with publicly available information. The formal interviews were fully transcribed and data from informal interviews and participant-observation was protocolled according to the methods described in (Babbie, 2013). The data was then coded and analyzed using software for qualitative data analysis.

4 Analysis

4.1 System structure

The flywheel innovation system is composed of several actors, networks and institutions. First, *actors* include flywheel manufacturers (presently about ten), technical universities and research centers (presently about six) and several industry associations that promote renewable energies and energy storage. Second, the *system* is characterized by the absence of formal industry networks. Nevertheless, several learning networks were initiated in the past years, which took the form of state-funded research projects involving industry partners. While there is knowledge exchange between academic institutions, transfer to the industry is very limited. Third, In terms of *institutions*, a difference between grid and off-grid application needs to be made. In the first, a rich and complex regulatory environment guides the operation of the power grid. By extension, these laws and rules also apply to energy storage. Then, energy storage technologies receive increasing political and public support as they can enable further expansion of renewable energy generation, however battery storage is politically strongly favored, leaving little space for alternative technologies. In mobile applications (mainly road traffic), storage can help to drastically improve the performance of existing internal combustion engines and thereby reduce greenhouse gas emissions. However, at a policy level, battery-powered electric vehicles are favored. In sum, the TIS includes members of the entire flywheel value chain but the actors are at present poorly organized and the existing institutional environment is rather disadvantages this promising technology.

4.2 Individual system functions

Function 1: Knowledge development and diffusion

In the German flywheel TIS, technological knowledge development is taking place at several research institutes. The research focuses on fundamental physical, mechanical and electrical features. The diffusion among research institutes is facilitated by several conferences (7 ongoing), at which the flywheel technology receives attention. Whereas knowledge development and exchange is happening in scientific arenas, several experts consider that transfer to industry is insufficient. Furthermore knowledge co-creation and diffusion between manufacturers is poor. A possible explanation is that the technology is close to market introduction and therefore entrepreneurs fear of industrial espionage and are reluctant to participate with other firms in research projects. Consequently, an important gap between fundamental and practical knowledge is observed.

Function 2: Influence on the direction of search

No univocal direction of search is observed. In fundamental research, the efforts are concentrated on several types of flywheels, which distinguish themselves with the level of integration, energy density (which depends on the density of the rotor and its rotational speed), the type of bearings, the shock resistance, etc. These developments are to some extent complementary but also lead to different type of flywheels (see previously introduced Figure 1) that fit different applications. In terms of application, these developments results in two broad categories of flywheels that differ in the ration of power stored on power output. This means that some flywheels are excellent at delivering an immense amount of power during a very short time period (< 1 minute) and others at delivering power over a longer time period, up to 12 hours. A third category can be distinguished: small, shock resistant flywheels that can equip automobiles, trains, trucks or mobile machines to recover breaking energy. The markets for these various types of flywheels are discussed below. The multitude of development trajectories has a negative overall impact on TIS development, as it dilutes resources and increases the total number of required experiments for growth and maturation of the TIS.

Function 3: Entrepreneurial experimentation

An interesting landscape of entrepreneurial experimentation is observed. It is composed of approximately fifteen firms, of which two kinds can be distinguished. The firms of the first kind are small and just about to be established. They typically employ a handful of employees and suffer of strong, chronical financial difficulties. The second kind is composed of established engineering and manufacturing firms who develop flywheels as part of their internal R&D. Only one large firm (approx. 800 employees) entirely bases its commercial success on the flywheel technology for uninterrupted power supply (UPS) applications.

The experiments of these firms reflect the diversity of technological direction of search. Indeed, firms experiment with various types of flywheels (see previously introduced Figure 1) and design attributes such as low and high-speed, active and passive magnet bearings and rotors made of steel and carbon fiber. They also target them at all identified markets (described in next section). Therefore, even though the absolute number of firms involved is small, the experiments are quite diverse and cover a large part of the technical design options and markets. However, as the absolute number of experiments are small, entrepreneurial experimentation appears dispersed and, from an industry perspective, without focus.

Function 4: Market formation

The formation of markets is determined by the various applications of the flywheel. In essence, they can be in a stationary (grid connected) and mobile (off-grid) environment. Typical stationary applications include the storage of energy, the stabilization of the power grid and as power buffers (to flatten energy production and consumption profiles). In the mobile environment, flywheels are typically used in (hybrid) electric vehicles to recover breaking energy, either to reduce fuel consumption or provide an extra power boost (in motorsports). Based on these applications, five markets with very different potentials of future development can be identified: Control power, Grid compensation, Uninterrupted power supply (UPS), Renewable energy home storage and Kinetic Energy Recovery Systems (KERS) (Table 2 Possible future markets for the flywheel energy storage.

Table 2 Possible future markets for the flywheel energy storage

Relevant markets	*Description of the storage application*	*Market potential for flywheel technology*
Control power	Make available power to balance and stabilize the grid, so called control or balancing power.	Low, because the regulatory framework in Germany disadvantages the use of power storage in markets for control power.
Grid compensation	Local power compensation at some strategic nods of the grid.	Limited, because the market size is very small (only several dozen applications in Germany)
Uninterrupted power supply (UPS)	Improvement of power quality at end-users, especially to assure interruption free power supply of critical application, such as airports, hospitals or data centers.	Low, as the market is mature, highly competitive, witnesses a slight decrease in sales volumes and faces a strong competition with other technologies (batteries).
Renewable energy home storage	Storage home generated photovoltaic power (bridge the production and consumption gap; day-night load shift).	Low, despite being a growing overall market, because strong competition with more economical second-hand batteries from electric vehicles is foreseen.
Kinetic Energy Recovery Systems (KERS)	Recovery of breaking energy in vehicles (both light and heavy weight) with a stop-and-go drive profiles. KERS can also be used in special machinery such as mobile cranes, etc.	High, but the development costs (especially the for the required safety certification) is very high (estimated at approximately 30 million Euros), which prevents many firm from market entry.

In sum, four out of the five markets have a small potential of development and the last one is constrained by important market entry barriers. Further, as the markets are all very different, the efforts of the firms to develop application-specific prototypes (and later a product) are strongly diluted.

Function 5: Resource mobilization

Resource mobilization is constrained in several manners. First, firms experience difficulties to access seed and start-up funding. Demonstration project would help, but firms experience difficulties in funding demonstrators. Second, public funding could support further development. However, development takes place largely at small firms who face difficulties to access grants, because they lack awareness about funding possibilities as well as resources and expertise for the application procedure. Thus, most firms struggle to find the necessary financial resources to bridge the gap between the demonstrator and niche markets.

In addition, the development of flywheels is constrained by the lack of qualified human resources. Indeed, the development of flywheels requires not only in-depth mechatronical (i.e. mechanical, electrical and IT) engineering knowledge, but also application-specific knowledge for the integration of the storage component into larger technological systems (e.g. grid storage; hybrid electric vehicle), which, together, is hardly accessible to most small ventures. However, this situation is different in (publicly funded) fundamental research (e.g. on magnetic bearings), where sufficient financial and personnel resources are available. However, as already explained in function 1, knowledge transfer to small firms is difficult for competitive reasons.

Function 6: Legitimation

The legitimately of the flywheel technology is relatively low for two reasons. First, in the first two markets – control power and grid compensation, experts disagree on the need for storage in the context of the German energy transition. According to some experts, energy storage will only become necessary with an energy-mix of over 60% of renewable energy; a long-term scenario is the current mix contains approximately 30%. Options such as grid expansion are currently preferred. Second, in the other markets, a strong reluctance is observed because of several fatal accidents that involved flywheels in the past. End-users, being afraid of the mechanical high-speed systems, appear to strongly favor non-mechanical storage devices, such as batteries.

Function 7: Development of positive externalities

Several positive externalities are observed. First, in mobile applications, flywheels can contribute to the reduction of greenhouse gas emissions as they can reduce fuel consumption of up to 35%. Second, they can reduce noise emissions, particularly in the context of buses and duty vehicles with stop-and-go drive profiles. Indeed, flywheels can provide the energy for start-up, which reduces the use of diesel engines the noise related to its start-up. Finally, in grid applications, flywheels support the expansion of renewable energy and thereby contribute to reduce greenhouse gas emissions.

4.3 Overarching system dynamics

The analysis of the seven functions in the innovation system reveals two overall *negative* and one *positive* feedback loops that relate to the formation of markets. These dynamics are explained below using causal loop diagrams (Sterman, 2000) representing the relationship between functions. The diagrams read as follow: an arrow marked with the minus sign (-) indicates that the first function has a negative effect on the second. A plus (+) signals a positive influence. A circled plus indicates a reinforcing feedback loop and a circled minus a balancing feedback loop, which can have either *positive* or *negative* effect on the overall system.

Dynamic 1: Multiple applications hinder market formation

The first dynamic (illustrated in Figure 2) relates to the multiple directions of search and the impact on the (slow) formation of markets. The coexistence of search directions has two negative consequences. First, it leads to the emergence a dispersed entrepreneurial experiments are too weakly connected with each other, as they are situated along different search trajectories. As such, their number is to be positively evaluated, but because of their dispersion, too few experiments punctuate each trajectory. Second, multiple search directions hinder market formation, as each search direction relates to different technology applications. The invested efforts are diluted between several possible future markets and there overall market formation is hindered.

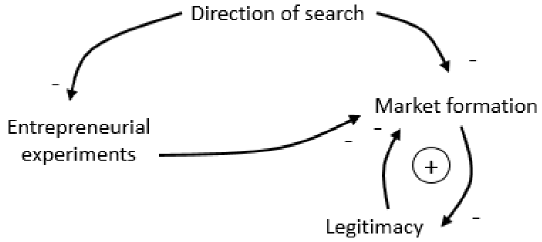

Figure 2 Dynamic 1: Multiple applications hinder market formation

What's more is that slow market development also has a negative effect on legitimacy. The negative image, which is due to past fatal accidents, persists over time, even though significant technological progress change the objective risks. Low legitimacy in turn negatively influences market development and therefore a self-reinforcing negative feedback loop can be observed.

Dynamic 2: Insufficient funding hinders market formation

The second dynamic (Figure 3) relates to the difficulty of mobilizing resource for the development of demonstration prototypes and the negative impact on the formation of markets. The most important difficulty, as expressed by TIS members, is to find the necessary resources to development pilot applications. For this step, prototypes are needed. As the resources are lacking, prototypes are not build and experiments do not multiply. Further, as several directions of search and possible future markets exist, the experiments appear dispersed (see dynamic 1) and market formation is hindered. In turn, the slow market development has a negative effect on actors' ability to mobilize resources. Indeed, as the market potential seems low and risks high, investors shy away. This loop is reinforced by the low legitimacy (see dynamic 1).

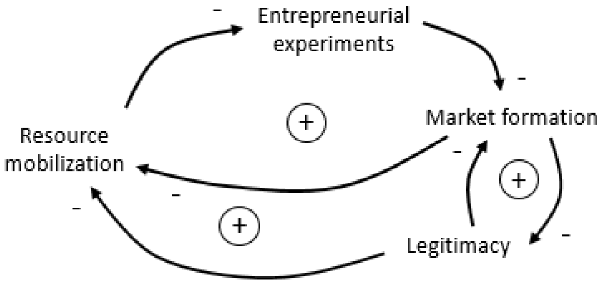

Figure 3 Dynamic 2: Insufficient funding hinders market formation

Dynamic 3: Positive (environmental) externalities support market formation

The third dynamic (Figure 4) is about the positive environmental externalities, as perceived by a potential future group of users, that increase the desirability of the technology and supports market formation. In the market of home storage, for example, a group of environmentally conscious consumers has expressed interest for environmentally benign storage technologies as replacement for batteries. The positive externalities of the technology (or rather the potential to drastically reduce negative externalities) increases its desirability, which might in turn ease resource mobilization, as investors might become interested. Investments might encourage entrepreneurial experimentation, which will likely support market development. Experts foresee the emergence of a positive self-reinforcing feedback loop, which is however constrained by other factors, in particular the predicted future availability of economical second-hand batteries.

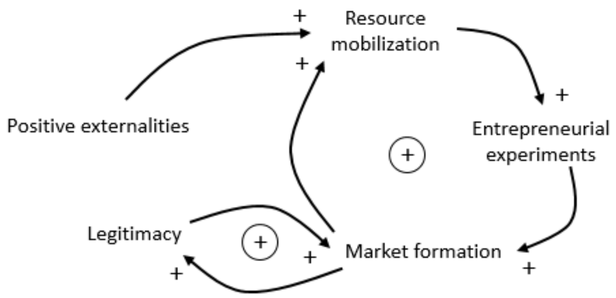

Figure 4 Dynamic 3: Positive externalities increases technology desirability and supports market formation

5 Discussion and conclusion

The aim of our research was to evaluate the stage of development and the performance of the flywheel innovation system in Germany. Our analysis revealed a mitigated situation, as several processes are malfunctioning and negative causal dynamics are observed. Central is the lack of consistency in the direction of search, important legitimacy issues, strong market segmentation, unfavorable market support mechanisms and low resource availability that prevent the TIS to grow from isolated experiments to niche markets.

The low performance of the TIS can be explained by two negative causal dynamics. First, the multitude of applications for the technology (dynamic 1) disadvantages the formation of markets. Indeed, from a market perspective, the five applications are very different, which reduces synergies between the different trajectories and disperses entrepreneurial efforts. Therefore, the pursuit of the five trajectories demands nearly as much efforts as for the development of five independent TIS. Second, the difficulty to access funding for demonstration prototypes (dynamic 2) hinders the formation of pilot markets. This is a typical issue of TIS in the formative stage. It is exacerbated by the presence of a multitude of complementary but disconnected trajectories, as just explained. However, a positive dynamic is also observed. The technology's positive environmental externalities attracts the attention of a consumer group, which might provide the necessary impulse for market formation. Indeed, environmentally conscious consumers show interest for this green technology as storage for exceeding self-produced photovoltaic energy. By sending positive market signal, this group might attract investors who could provide funding for the next steps in technology development. However, this dynamic did not yet materialize and prospects for market development remain meager, as technological competition is important.

The early stage of development of the TIS is surprising considering the age of the system. Even though the first scientific flywheel colloquium dates back to the 1970s, most efforts still go into fundamental research. What's more is that firms involved in technology development are mostly small, suffer of chronical financial difficulties and are driven by technology-believers with weak market orientation. Finally, while several markets were identified, few concrete steps towards market introduction were undertaken, prospects for market development remain low.

Our analysis provides answers to the low performance of the overall system and allowed to evaluate its current development stage. Further and most importantly, the analysis of the functions allow to gain an in-depth understanding of the processes explaining the low performance. However, an important shortcoming of our functional analysis is that it did not directly explain the absence of a window of market opportunity. Indeed, relevant and determining political aspects were not explicitly addressed, even though they play an important role in the German energy transition, as the expansion of renewable energy generation is strongly politicized. The fact that decisions are not only based on technological rationality might explain that some technologies are politically favored over others, even though they clearly underperform in the given application context. Furthermore, the development of the flywheel TIS is also influenced by other TIS, as suggested in theory by Markard and Truffer (2008). Flywheels are in strong competition with batteries, which development currently receives an important support both form politics and multi-national companies (e.g. from the chemical and automotive industries). The interaction between the two TIS is not necessarily negative, as the important lobbying for batteries also liberates funding for research on energy storage technologies in general, of which flywheels might possibly also benefit. The analysis of this complex interaction goes beyond the scope of this study and should deserves attention in future research.

6 Limitations and future research

The present research is limited by its scope. Indeed, and important part of flywheel development happens in the United-Stated of America. Future research could therefore compare the German with the US flywheel TIS. To account for the competition between batteries and flywheel, future research should also compare the flywheel with the battery TIS.

7 Implication for practice

This paper draws the attention to a new and promising TIS that is forming in the energy storage context and informs policy makers on its key processes and reveals possible leverages to influence its direction. Finally, by highlighting in what areas flywheels can be applied and by evaluating related markets, this research represents an input to the strategic decision-making process of interested firms, which appears to be particularly welcomed by TIS members who are confronted with limited resource availability and weak regulatory support.

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