Experimentations in emerging innovation ecosystems: specificities and roles. The case of the Hydrogen Energy Fuel Cell

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Experimentations in emerging innovation ecosystems: specificities and roles. The case of the Hydrogen Energy Fuel Cell[1].

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Abstract: Little research has focused on the way an innovation ecosystem emerges and specifically what processes and tools support it. We argue that as in innovation development processes, experimentation may generate knowledge and reduce the uncertainties associated with this emergence. Based on a longitudinal study of hydrogen energy solutions that require a novel ecosystem, we outline four specificities of the experiments performed, designated as complete solution experiments, and their role in this emergence. They (1) involve all the players required so as to deliver and operate a complete solution, (2) target real customers using the innovation in real conditions over a significant period of time, (3) are highly refined (components and complements are representative of an industrial offer) and (4) are transparent on how the data generated will be exploited and shared with all the players who commit to the experiment, who are thus assured that they will acquire validated information.

Keywords: systemic innovation; innovation ecosystem; experimentation; prototyping; ecosystem emergence; complete solution experiment; fuel cell; hydrogen energy.

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Below a summary of the article and a short video
https://mailchi.mp/hec/energy-transition-innovation-ecosystems-netflix-7ovmae28m4?e=36f77f7062

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1 Introduction

An innovation ecosystem is a collaborative arrangement through which firms combine their individual offerings into a coherent customer-facing solution (Adner, 2006). It has raised several questions that have been addressed by the literature, such as how to coordinate partners and align their incentives (Iansiti and Levien, 2004; Cusumano and Gawer, 2002), what are the associated risks (Adner, 2006), how to map the innovation ecosystem (Adner, 2012), etc. However, few research works have focused on how innovation ecosystems emerge and specifically what processes and tools support such emergence.
We consider that the emergence of innovation ecosystems is worth studying for two reasons. First, research on innovation management increasingly stresses the importance of the ecosystem (Nambisan and Sawhney, 2011, for example). Second, the emergence of the ecosystem is critical for a wide range of systemic innovations (Chesbrough and Teece, 1996) or complex innovations (Dougherty and Dunne, 2011) such as the electric vehicle (von Pechman et al. 2015) or more generally new types of energy (Dougherty and Dunne, 2011).

We propose to qualify an ecosystem as emergent when the perimeter of the overall offer is not stabilized, the contributors to this offer are not all identified, and the rules between the contributors are still not entirely defined. Within this definition, many uncertainties therefore remain about the innovation and the ecosystem providing it.

Proceeding by analogy with the literature on innovation development processes, we argue that experimentation, which plays a critical role in development processes, may also play a role in the emergence of an innovation ecosystem. Indeed, Thomke (2003), among others, showed that experimentation is a way of reducing uncertainties and supporting knowledge creation and combination between actors from different specialties. As various kinds of experimentation have been pinpointed in this literature, we expect that experimentation supporting uncertainty reduction in the emergence of ecosystems might exhibit specific characteristics that could be studied based on the dimensions highlighted by Thomke (2003).
Therefore, our research questions focused on experimentation in the context of the emergence of an innovation ecosystem: what are the characteristics of the experiments performed during the emergence of the innovation ecosystem? To what extent do these experiments contribute to the ecosystem's development and what kind of knowledge can be generated based on these experiments?

We addressed these questions by studying a single case: the innovation ecosystem built for developing Hydrogen Energy (HE) solutions which produce electricity from hydrogen. We chose this case because of its relevance to our research questions. Indeed, this is an innovation that requires the involvement of several players: fuel cell producers and their suppliers (membranes and other components), providers of hydrogen and its packaging, firms specialized in the logistics and transportation of the gas, providers of devices that transform and adapt the electric power into a usable one, etc. Another critical player is the public authority, which contributes by regulating the transportation of such an explosive and flammable gas and incentivizing the use of this low-carbon-emission source of energy. All these players complement each other in providing an effective HE solution, as they are knowledgeable about subparts that need to be integrated. None of them masters the overall solution. Thus developing and commercializing such a solution creates interdependencies between these actors that belong to various sectors and have not developed relationships in the past. Hence, according to Adner (2006), HE is an innovation ecosystem because it is a collaborative arrangement through which firms combine their individual offerings into a coherent customer-facing solution. It allows the firms involved to create value that no single firm could have created alone. Gawer and Cusumano (2008) suggested that new energy sources such as hydrogen fuel cells could become ecosystem platforms.

We studied the emergence of this innovation ecosystem (Koenig, 2012; Gulati et al., 2012) in real time over 18 months. During that period, ten hydrogen energy solutions that we designate as Complete Solution Experiments (CSE) were delivered by the ecosystem. These prototypes supported the generation of knowledge that no partner could have developed alone, such as the operating conditions and the resulting actual costs, the actual benefits for the customer, the context of usage and the overall functional performance delivered on site. We argue that a CSE is an experimentation of both the innovation and the ecosystem: it is an ecosystem prototype.

Below we outline the specificities of the experiments deployed and their role in the emergence of the innovation ecosystem. The experiment (1) involves all the players required so as to deliver and operate a complete solution, (2) involves real customers using the innovation in real conditions over a significant period of time, (3) is highly refined (the components and complements are representative of an industrial offer) in order to convince the customer to take part in this experimentation, and (4) ensures that all the players who commit to the experiment know upfront how the data generated will be exploited and shared and are assured that they will get validated information.

With this research we contribute to the literature on innovation ecosystems that has not addressed this emergence phase. We also contribute to the literature on experimentation in innovation processes, which is mainly firm-centered and has not studied innovation developed within an ecosystem.

The article is structured as follows. In the literature review, we synthetize the main characteristics of innovation ecosystems as they appear in previous works. We also look at research into the role and characteristics of experimentation and prototypes in developing innovation. Based on this background, we articulate the theoretical framework that will be used as a grid of analysis of the case study and our research questions. The research setting and the research design are then presented. Finally, data are presented following the theoretical framework and discussed based on this literature.

2 Literature review and research questions

In the first part, we specify the notion of ecosystem as developed in the literature and the definition that we adopt. We then focus on the innovation ecosystem and underline the risks to be addressed in the development of innovation within an ecosystem, and the knowledge required to reduce these risks. In the third part, we synthesize the research work on experimentation in innovation processes and its role in reducing uncertainties and risks. Progressively we highlight the main elements of the literature that we aim to specify and the gaps that we intend to address. As a conclusion, we articulate our research questions.

2.1 Ecosystem and focal firm

Firms are increasingly entering into collaborative relationships, leading some researchers (Gulati, Puranam and Tushman, 2012; see the June 2012 special issue of SMJ) to call for a conceptual transition from the organization to the ecosystem composed of many legally autonomous organizations linked together. Ecosystem members are suppliers, distributors, outsourcing firms, complementors (providers of related products or services) and more

generally any organization that affects and is affected by the creation and delivery of a company's own offering (Iansiti and Levien, 2004). These members can be business firms, nonprofit foundations, public institutions and other agents (Dougherty and Dunne, 2011).
The notion of ecosystem refers in the literature to various definitions that several authors (Iansiti and Levien, 2004; Koenig, 2012; Gulati et al. 2012, etc.) have tended to organize into typologies. Koenig (2012) suggests a typology based, on one hand, on the centralization/decentralization of critical resources within the ecosystem and, on the other, on the form of interdependence between the members, either pooled or reciprocal as distinguished by Thompson (1967). A specific type of ecosystem is thus characterized by reciprocal interdependencies between the members and by the presence of a focal firm that masters and centralizes critical resources. This type is similar to the one identified in the typology of Gulati et al. (2012) and called the "managed ecosystem". Their typology is based on the degree of hierarchization of decision-making on one hand, and the openness of membership on the other. A managed ecosystem has three characteristics: a focal firm, heterogeneous members, and rules.
The leader or the focal firm co-envisions and co-manages the evolution of the ecosystem among the members, ensuring the coordination and the alignment of their interests. It thus plays a critical role. The focal firm, or ecosystem keystone as labeled by Iansiti and Levien (2004), aims to improve the overall ecosystem, ensuring its own survival and prosperity. This central player creates value within the ecosystem and shares it with the other participants in order to ensure the sustainability of the ecosystem.
The heterogeneous members contribute together, directly or through indirect impacts (such as the public authorities that issue regulation and policy), to the delivery of an overall offer or a complete solution. Gulati et al. (2012) highlight the fact that most companies inhabit ecosystems that extend beyond their own industries.
The rules and interfaces are defined in order to put together contributions and to ensure their compatibility, leading to the design and the delivery of an overall offer.

In this research, we will focus on this kind of ecosystem, the managed ecosystem, defined by the combination of the characteristics set out above and outlined by Koenig (2012) and Gulati et al. (2012). To date, the literature on this ecosystem has mainly studied the role of the keystone player once the ecosystem is structured (Iansiti, 2004). However, Moore (1993; 1996) suggested a life cycle perspective differentiating three phases of an ecosystem's development: birth, expansion, predominance and renewal. Birkinshaw, Bessant and Delbridge (2007) emphasize the difficulties of network building. More recently, there has been debate about whether ecosystems emerge spontaneously or are structured and planned (Dougherty and Dunne, 2011).

We propose to qualify an ecosystem as emergent when the perimeter of the overall offer is not stabilized, the contributors to this offer are not all identified, and the rules between the contributors are still not entirely defined. We argue that ecosystem emergence has been under-studied in the literature and intend to address that gap in the specific case of a managed ecosystem.

2.2 Innovation and ecosystem

Studying the emergence of ecosystems is critical specifically for systemic innovations that require the development of novel ecosystems, such as the electrical vehicle (von Pechman et al. 2015) or more generally complex innovations as described by Dougherty and Dunne (2011). Indeed, research on innovation management increasingly stresses the importance of

the ecosystem. Nambisan and Sawhney (2011) show a shift from firm-centric innovation to network-centric innovation. Chesbrough and Teece (1996) stress that in the case of systemic innovation the benefits “can be realized only in conjunction with related, complementary innovations”. Adner (2006) emphasizes the interdependencies between firms in the development of innovation and highlights the role of the “innovation ecosystem”. According to him, such ecosystems allow firms to create value that no single firm could have created alone. He defines the innovation ecosystem as the collaborative arrangement through which firms combine their individual offerings into a coherent customer-facing solution. He stresses the role of the focal firm in reaching such an agreement. The innovation ecosystems he analyzes have the properties of a managed ecosystem as defined above, with a focal firm and strong interdependencies between the members.
Focusing on innovation management processes, Adner (2006) identifies three types of risk that characterize innovation ecosystems and should be managed: (i) initiative risks (traditionally associated with the innovation development process, such as feasibility, benefits for the customer, etc.), (ii) interdependence risks (or co-innovation risks associated with the uncertainties of coordinating with complementary innovators) and (iii) integration risks (associated with the adoption process across the value chain and thus also called adoption chain risks). Whereas interdependence risk is rooted in the existence of complementors, integration risk is linked to the existence of intermediaries between the innovation and the final customer. Assessing this risk requires the identification of those intermediaries and the evaluation of the costs and benefits of innovation adoption for these players.
In order to tackle these risks and reduce the uncertainty, the focal firm needs to acquire various types of knowledge: technological knowledge in order to develop the innovation, relational knowledge in order to develop the relations between the members of the ecosystem, and structuration knowledge in order to develop the global offer (Loilier and Malherbe, 2012). These last two types of knowledge are referred to as “ecosystemic competencies” by Moore (1998).

The literature on innovation ecosystems has addressed neither how the focal firm acquires this knowledge, nor the emergence of a novel ecosystem required for the development and diffusion of an innovation. We intend to address this gap.

2.3 Experimentation in innovation processes

The duality between risk and uncertainty on one hand, and knowledge acquisition on the other, is central to innovation processes and has been highlighted by several authors (Midler, 1993; Nonaka, 1994; Lynn et al., 1996; Loch et al., 2006). The literature on new product development (NPD) (Ulrich and Eppinger, 2003; Crawford and Di Benedetto, 2004; Schrage, 2000, etc.) has emphasized the role of physical artifacts as a means to expand knowledge and reduce uncertainties.
In his seminal work, Thomke (2003) showed that experimentation supports the reduction of uncertainties through the generation of knowledge. He analyzes how prototypes enable the validation of technical options for an innovative solution as well as functional performance, robustness and manufacturability. Prototypes are conceptualized as boundary objects (Star and Griesemer, 1989) around which the contributors and future users can interact. Indeed, the actors involved in a development team belong to different functions of an organization and have various domains of expertise: they belong to different “thought worlds” (Leonard-Barton, 1995; Dougherty, 1992; Carlile, 2002). Prototypes support the discussion between these actors through the explicitation of the constraints, needs, and difficulties that they may

encounter either in designing, manufacturing, selling or using the innovation. It has been shown that these interactions lead to knowledge combination and enable actors to overcome difficulties related to cooperation between people with different competencies and backgrounds (users, customers, suppliers or complementors).
In the same line of thought and focusing on radical innovation, MacMillan and McGrath (2009) underlined the fact that experimentation enables risks reduction by transforming assumptions articulated during the phase of opportunity identification into validated knowledge by following a discovery-driven process that they documented in detail.
More recently, based on a review of research on prototypes in the design literature, Rhinow et al. (2012) differentiated three main roles associated with prototypes during a design process. First, it triggers user feedbacks. Second, it favors an improved team experience: it is a way to create bonds and links between the team members. And third, it helps to visualize the focus of exploration. Prototypes are means of communication to show progress and obtain commitment from the various stakeholders and support from members of the organization. Ben Mahmoud-Jouini and Midler (2014) argued that the role of prototypes varies according to the phases of the innovation process. It stimulates creativity in the early phase, whereas it is used to demonstrate and explore the potential of technologies or ideas during the development phase, and finally, at the end of the process, it is used to test and validate the specifications defined. Therefore, the artifacts used as prototypes differ according to the phase of the process.
Various experiments occur along the development process and have been outlined in the literature. Thomke (2003) suggests (i) performing experiments early in the innovation process in order to reveal what does not work before substantial resources are committed, (ii) experimenting frequently while balancing the cost generated, (iii) combining new and traditional technologies in experiments in order to enjoy cheap and fast experimentation while avoiding performance gaps, (iv) experimenting quickly, (v) failing early and often because this generates knowledge and learning.
The following characteristics help differentiate the kinds of prototypes or experiments designed (Thomke, 2003): (i) fidelity (degree to which the experiment represents the real product), (ii) degree of finalization, (iii) cost of designing, building, running and analyzing the experiment, (iv) duration of the experiment, (v) strategy of experimentation (parallel or in series), (vi) timing of its implementation in the development process, and (vii) elements to be tested through the prototypes and with which stakeholders, etc.

Based on these research works, we argue that experimentation could play a role in the emergence of an innovation ecosystem. As stated above, it has been shown that experimentation enables uncertainty reduction in innovation processes and supports knowledge development and knowledge combination between actors that have different competencies. However, the majority of the research work on experimentation in innovation processes is firm-centered and does not specifically study innovation developed within an ecosystem. We intend to address this gap as well. As various kinds of experimentation have been pinpointed in the literature, we expect that experimentation supporting uncertainty reduction in the emergence of ecosystems exhibits specific characteristics that could be studied based on the dimensions highlighted by Thomke (2003).

2.4 Theoretical framework and research questions

The table below summarizes issues that we retained from the streams of research and we considered as relevant for the study of the emergence of an innovation ecosystem.

Table 1 Literature review recap

Characteristics of a managed ecosystem (Gulati et al., 2012; Koenig, 2012).	Risk associated with the development of an innovation ecosystem (Adner, 2006; 2012).	Characteristics of the experiment undertaken during the innovation development process (Thomke, 2003).
- A focal firm - Heterogeneous players that contribute together to the delivery of an overall offer, - Rules and interfaces in order to integrate the contributions and to ensure their compatibility.	- Initiative risk associated with the innovation development process, - Co-innovation or interdependence risk associated with the coordination of the players, - Integration risk associated with the adoption of the offer through the value chain.	- Fidelity (degree to which the experiment represents the real product), - Degree of finalization, - Cost (designing, building, running and analyzing the experiment), - Duration of the experiment, - Strategy of experimentation (parallel or in series), - Timing of its implementation in the development process, - Elements to be tested through the prototypes and with which players.

Our aim is to address a twofold gap in the literature: that on innovation ecosystems on one hand, and that on experimentation in innovation processes on the other.
As mentioned above, little research, apart from Gawer and Cusumano's work on Intel (2008), have studied the emergence of ecosystems. Research on innovation ecosystems has seldom studied their emergence and specifically what processes and tools enable the reduction of the risk associated with their development.
Based on the literature on innovation processes, we argue that experimentation, as a means to create knowledge, may play a role in the emergence and development of an innovation ecosystem by reducing the associated risks.
Therefore, our research questions are the following. In a context of the emergence of an innovation ecosystem, what are the characteristics of the experiments undertaken? To what extent do these experiments contribute to the innovation ecosystem development? What kind of knowledge can be generated based on these experiments?

3 Method: Research setting and research design

In order to address these questions, we conducted a qualitative, longitudinal, and inductive study of a single case. We focused on the case of innovative solutions that produce electric energy by using hydrogen (HE). More specifically, a big firm (designated as GP in the following) coordinated an initiative dedicated to designing, developing and marketing HE solutions involving various players. We will address these questions through the specific case of a managed innovation ecosystem characterized by a focal firm (GP) that centralizes a critical resource and has reciprocal interdependencies with various players in order to deliver an overall offer. We had the opportunity to study the construction of this ecosystem in real time over a period of 18 months.
In the first section below, we detail the research setting: the systemic character of this innovation, why it required the emergence of a new ecosystem and the specific role taken by GP that represented our point of entry in the ecosystem. In the second section, we present the research design: the research site itself, data collection and analysis.

3.1 Research setting: the Hydrogen Energy case

Despite the fact that fuel cell technology has long been described in the scientific literature, developing commercial solutions using this technology still requires innovation. The reasons are at least of two kinds. One is economic and relates to the production costs of fuel cells (very expensive materials are used in crucial components), and the other is related to safety issues regarding the packaging and distribution of hydrogen (a flammable and explosive gas under certain conditions). It thus requires the development of innovations in the field of fuel cells themselves (the material used for crucial components in order to enable cost optimization) on one hand, and in the field of packaging and distribution of hydrogen to tackle the safety issues on the other, not to mention innovation associated with the usage of this source of energy. Further, it requires the development of market knowledge so as to elaborate value propositions for HE solutions that may convince customers to adopt them. This form of energy can be seen as a new offer that brings new values on top of emissions reductions, such as noise reduction, mobility or flexibility enhancement.

Therefore, HE is a systemic innovation, as it goes far beyond simply selling a fuel cell machine that transforms hydrogen into electric power. It requires several complementary products. Hydrogen packaging should be adapted so as to deliver the gas at the quantity and with the frequency appropriate to this usage, specific electric converters are needed, regulation should be adapted to allow the usage of hydrogen in various situations, etc. Dougherty and Dunne (2011) showed that such innovation requires the structuration of an ecosystem. This involves several heterogeneous players belonging to different sectors.

3.2 Research design: research site, data collection and analysis.

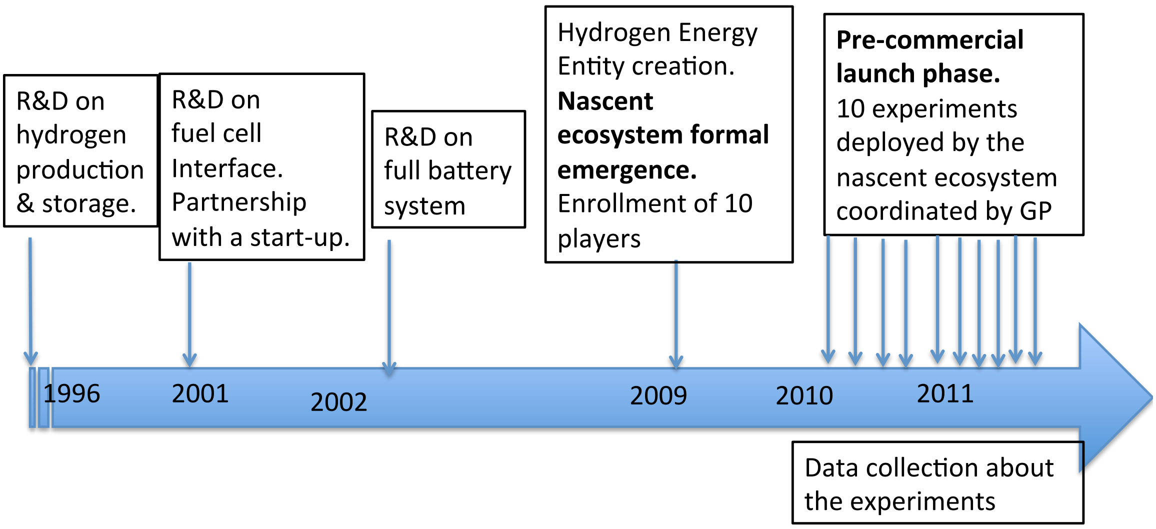
In order to address our research questions, which involve understanding the emergence of innovation ecosystems and more specifically exploring the potential and role of experiments in this emergence and their characteristics, we decided that the choice of a single intensive case study was worthwhile in terms of access to unique data and the chance to explore new theoretical questions (Eisenhardt, 1989; Yin, 2009). Indeed, the strength of case study research is its ability to produce novel theoretical insights stemming from case-specific contextualized findings (Eisenhardt, 1989; Galunic and Eisenhardt, 1996; Eisenhardt and Graebner, 2007; Sigglekow, 2007; Hoon, 2013).

Research Site

More specifically, we analyzed the actions undertaken by an entity developed within GP and dedicated to the development of this HE ecosystem. GP is a multinational corporation present in 80 countries, counting more than one million clients and with 15.4 billion euros in revenue in 2014. It is a worldwide leader in hydrogen production and delivery. Since the end of the 1990s, GP has initiated and supported several research projects on HE solutions because such applications appeared to be promising opportunities for the company's hydrogen business. However, the research undertaken during that period showed that the integration of the gas supply with fuel cell technology was a big challenge that required the involvement of several players. Based on the technological and market knowledge developed, in 2009, GP set up a specific organization and enrolled ten players representing 150 persons overall, 20 within GP, in order to work on a publicly aided program with a project dedicated to the pre-commercial launch of HE solutions. These players included three private firms in charge of the fuel cell, its critical component and the cartridge, and seven research centers and associations involved in the development of the HE. The public agency committed to fund a third of the overall budget (€200M) while the players funded the remaining part. Six years later, niche markets of early adopters were served, such as remote sites for telecommunication antennas, for example. Because of the competencies of this firm, the resources it invested and the coordination role it had, we consider GP as a focal firm of a managed ecosystem involving other partners, in line with Koenig (2012) and Gulati et al. (2012).

The figure below presents the different steps GP went through in order to develop this innovation. Our focus will be on the phase called the pre-commercial launch that started more than 10 years after the first research programs on HE solutions the firm invested in. At that stage, several actors had committed to the development of a coherent solution that could be proposed to potential clients. We consider that stage as the formal emergence of the ecosystem. The perimeter of the overall offer is not stabilized yet, the contributors to this offer are not all identified and the rules between the contributors are still not entirely defined. However, ten different contributors committed to developing HE solutions and signed a formal agreement. We call this group of actors the nascent ecosystem, as a reminder that evolutions in this group of actors may occur throughout the emergence phase.
Our longitudinal research took place during that phase and lasted 18 months (cf. fig. N°1). Several experiments were designed and performed by the focal firm and its partners in order to garner an overall approach to the HE solutions. We focused on these experiments that represented our point of observation and object of analysis of the ecosystem's emergence. We will characterize these experiments in the results section.

Figure 1 Positioning of our research and data collection in the timeline of R&D on HE within the firm

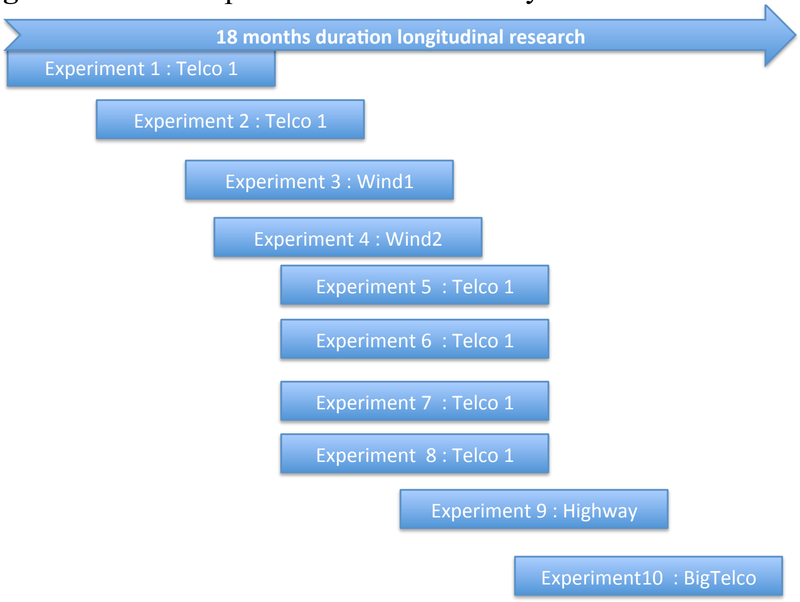


Data collection

The data on which the research is based were collected mainly through interviews with people within GP. The interviews were complemented by documents (internal to the firm and to the ecosystem and public documentation on HE). The data collection was structured in two phases and lasted from April 2010 to July 2011 (cf. Figure N°1).
In the first phase, we conducted 12 interviews of 90 minutes each on average with people in GP who have been involved in projects related to the development of HE solutions. We also had access to various documents about these research projects. This enabled us to delineate the main phases of the innovation process for GP and to highlight when and how various stakeholders were progressively identified.

In the second phase, we focused on the ten experiments designed and executed by the nascent ecosystem (cf. Figure N°2). We could thus gather information about the feedback that the actors got from the operation of these experiments.

Figure 2 The 10 experiments undertaken by the nascent HE ecosystem



Each experiment was carefully analyzed: the participants, the objective, the assumptions surrounding the technology, the markets, the usage, the value creation and breakdown, the results, i.e. the data collected during and after the experiment, and the knowledge generated (cf. table N°3 about the experiments in the data section). Our main source regarding these experiments was interviews with people from GP. The main upside of this approach is that it provides access to detailed and specific data from the critical player in the ecosystem, while the downside is that it only gives a partial perspective. In order to balance this perspective with that of the other players involved, we interviewed several people in GP for their close relationships with different actors of this nascent ecosystem. We also had access to documents about the overall program and about the different players involved.

For each experiment, six interviews on average were conducted with the following persons within GP: the HE program coordinator and the members of the HE team in charge of coordinating one of the program's areas (H2 production, H2 transportation and conditioning, design of the fuel cell system, analysis of market segment and value proposition, industrial scale up, commercialization, etc.). This second phase of data collection represented 60 interviews.

Besides the interviews with the players, the researchers had access to a business model tool (Excel spreadsheet) and a database that was designed by the focal firm and included a technical description of the solutions experimented with and economic data about their cost of operation. Each experiment generated data that were analyzed with this tool. It was also used for capitalizing on the knowledge generated. Hence, many interviews involved a discussion on the feedback from the experiments as compiled in this tool.

In addition, mappings of the nascent ecosystem were designed and shared with the HE coordinator when the experiments revealed the need to enroll new players, for example.

This extensive data collection was possible thanks to the strong involvement of a research assistant with whom the researchers shared the data and organized very regular meetings.

On top of that, every six weeks, a meeting was organized with the HE project manager within GP, the research assistant and researchers. During these meetings, the progressive

understanding of the main steps of the emergence of the ecosystem was shared as well as the role played by the experiments.
Thanks to these data, we could gain deep insights into the role of experiments in the emergence of the innovation ecosystem.

Data analysis

In order to analyze the data based mainly on transcripts of interviews and documents, we built a grid of analysis based on the literature review and composed of three main elements: dimensions for describing the emergence of the ecosystem, dimensions for characterizing experiments, roles of experiments in innovation processes.

Table 2 Grid of analysis of the data

Dimensions for describing the emergence of the ecosystem	Dimensions for characterizing experiments	Roles of experiments
Perimeter of the overall offer	Timing in the innovation process	Knowledge generation (transformation of assumptions into validated knowledge, gathering user feedback, etc.)
Contributors involved	Players involved	Knowledge combination
Rules defined between the contributors	Elements to be tested and knowledge expected	Improved team experience
	Cost (designing, building, running, analyzing the experiment)	
	Fidelity	
	Refinement	
	Duration of the experiment	

3 Case study

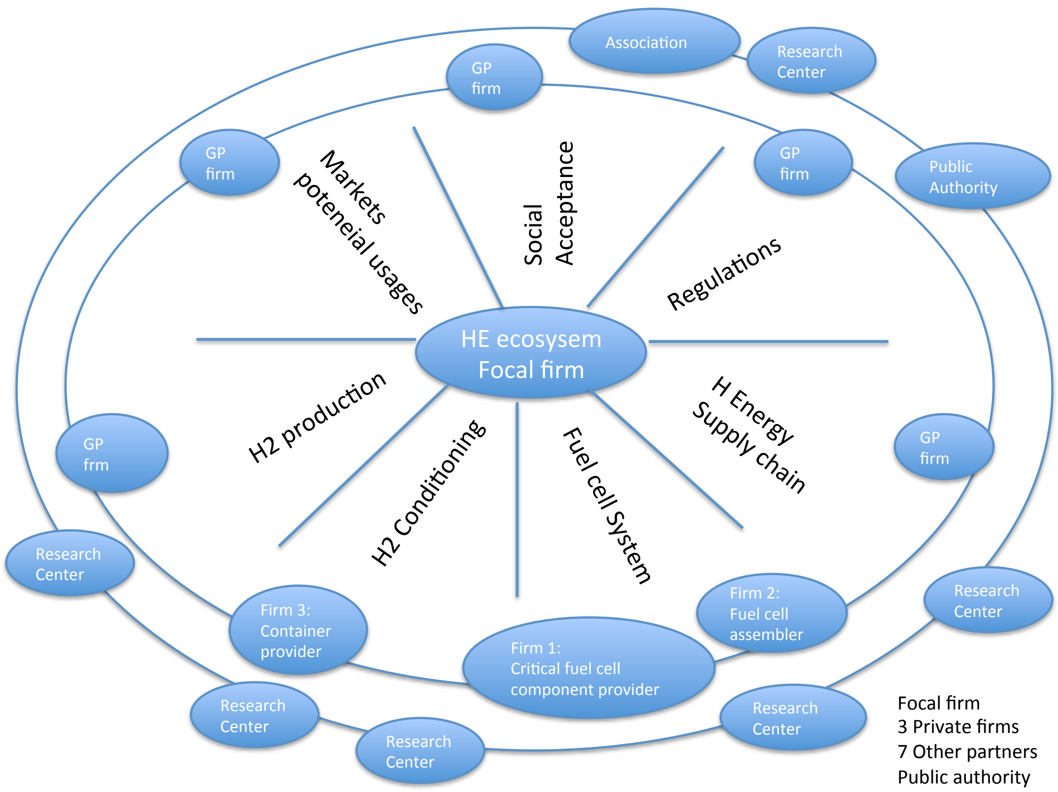
In the following, we present the case study: the nascent ecosystem as it was when the publicly aided initiative started. Then we present the experiments deployed resulting in an evolution of this nascent ecosystem thanks to the involvement of new players enrolled, and finally the types of knowledge generated.

3.1 The nascent HE ecosystem

As mentioned in the research setting section, several heterogeneous players are involved in the development of a HE solution (HES): firms developing the fuel cell and their suppliers (membranes and other critical components), and firms mastering hydrogen production and delivery (packaging, logistics). These players were not used to working together, had no previous business relationship or cooperation, belonged to different sectors and served different markets. Though each player has its own innovation trajectory they are all interested in the development of HES. As mentioned in the method section, the publicly aided program was an opportunity to pool together several actors interested in HES development who decided to take part in this program. The program was structured around seven work packages to leverage various competencies: about the solution's technology (H2 production, H2 conditioning and the fuel cell system), about the market, about acceptability (regulations and social acceptance) and about the HE supply chain.
The figure below (cf. Figure N°3) presents the actors involved and the domain in which they contributed. The focal firm has a dual role: coordinating the players on one hand, and being

involved in four domains among the seven. For that second role, itwill be designated as GP firm in the figure representing this set of actors that we consider as a nascent ecosystem for HES according to the definition that we adopted in the literature section. Indeed, many uncertainties remained at the launch of the program about technology, functional performance, cost, value perceived by customers, how they evaluate it, and the regulatory constraints.

Figure 3 The nascent HE ecosystem



3.2 The "Complete Solution Experiment"

Jointly these companies decided to deploy experiments involving fuel cell functional prototypes with real clients having specific needs to fulfill. The core players were a firm mastering a critical component of the fuel cell, the fuel cell assembler, the gas producer (GP) and a company that designed a specific cartridge for hydrogen.

These companies had previously developed several models for the technical performance of the fuel cell, the operating conditions, the cost and benefits of the HES, etc. These models were based on assumptions. The consolidation of these hypotheses in one unique model raised issues and questions about the business model in terms of the operation of such a solution: technology, cost, value proposition, distribution, etc. Therefore, in order to test the assumptions and acquire knowledge that could help address the open questions, the focal firm decided with the other players to develop experiments.

The experiments took place after each contributor had acquired enough knowledge of the subsystem they provide to commit to its technical performance and to anticipate its manufacturing and implementation costs. However, each contributor accepted to take part to the experiments in order to acquire the knowledge identified as missing at that stage and preventing them from a stronger commitment with the other contributors. Even though the

fuel cell technology itself was tested previously and even though the performance of the fuel cell over a long period of time can be tested in laboratory conditions, testing the overall solution required a full scale real experiment because the elements composing this solution needed to be coordinated and integrated. Furthermore, the experiments consisted of operating the solution with a real customer over a long period of time (several months).
Thus, compared to the business model designed at the very beginning of this phase when the players applied to the publicly aided program and consolidated their knowledge about HES, the experiment represented a second level of integration in real conditions involving real customers.

Several potential customers that might value the main attributes of HES (clean, quiet, no vibration, low maintenance (no rotating parts), low emissions, easy to install and rapid startup) had been identified. A first analysis of the markets that might potentially value this form of energy led to the identification of different usages related to four attributes of the HES offer: portability, flexibility, silence and low emissions on site. These usages include special vehicles such as forklifts in warehouses, remote sites such as areas not connected to the electric grid where telecom antennae are located, and actors needing portable power generation with low noise and/or emission levels (cinema shoots, rescue situations, etc.). Previously, such players looking for an alternative form of energy for a confined place or for a temporary usage (telecom operators, logistics firms, movie producers, etc.) had never contracted with the industrial companies involved in the development of HE solutions.

The focal firm jointly with the other actors involved decided to focus on one market among those previously identified: power supply to remote sites.
The objective of the experiment was to test whether the solution as a whole would meet the needs of the client (as a replacement of their previous solution, if any) in the long run, and whether it would present sustainable economic performances for the various players involved. Convincing the customer to participate in a full-scale test requires the offer of a functional overall solution. The solution would include a fuel cell that delivers the power and intensity needed and the required hydrogen supply. Furthermore, deploying an experiment with a real customer requires the design of a revenue business model such as a lease of the fuel cell and the payment of hydrogen consumption or a subscription to the overall service through the payment of a fixed lump sum.
At such an early stage, the fuel cell components and the hydrogen logistics were not yet optimized, so the costs of production and operation were high. Each experiment was thus an investment for each contributor involved, one that reflected their need to gain knowledge about the components of the solution they did not master themselves and more generally about the validation of the overall solution.

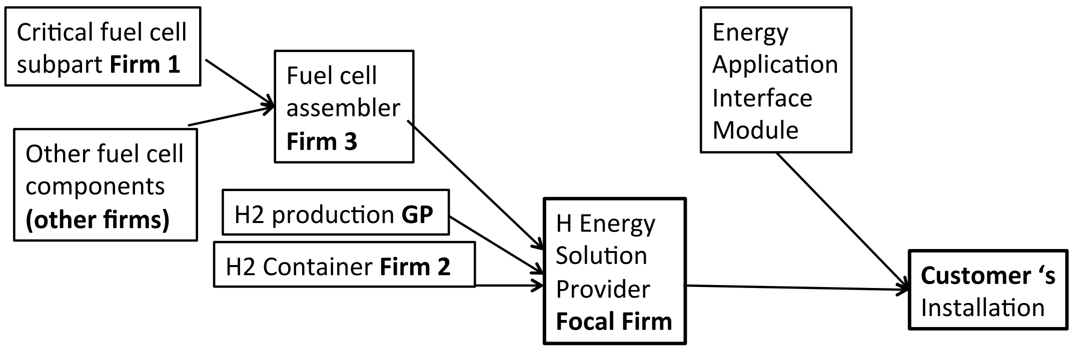
We propose to call these experiments a *complete solution experiment* (CSE) as they share several characteristics. They target the experimentation of the overall solution by involving all the contributors. It is a full-scale experiment that aims to test the integration of the different elements and thus needs to rely on all the components of the overall offer. Hence, on one hand, the CSE enables an exploration of the overall performance (functional, operating cost, etc.) reducing the risk associated with the system level of the innovation (the fact that the offer is composed of many components that interact together). On the other, it involves real customers, generating data on the context of usage and the economic conditions (cf. table N°4 for a recap of CSE characterization).
The CSE is an experimentation of both the innovation and the ecosystem: it is an ecosystem prototype.

Furthermore, compared to the prototyping and experimentation that were previously carried out by the players separately, these experiments are expected to generate knowledge on dimensions that no partner can develop alone, such as the operating conditions and the actual resulting costs, the actual benefits for the customer, the context of usage and the overall functional performance delivered on site.

3.3 Evolution of the nascent ecosystem due to the knowledge generated with the Complete Solution Experiments.

Over the course of 18 months, ten experiments were designed and carried out for the remote site market. For each experiment, Table N°3 summarizes the knowledge generated and the actions undertaken based on this knowledge.
Following the schematization suggested by Adner and Kapoor (2010), the firms involved in the HE offer at the start of the program can be represented as in figure N°4.

Figure 4 Representation of the nascent ecosystem before the launch of the experiments

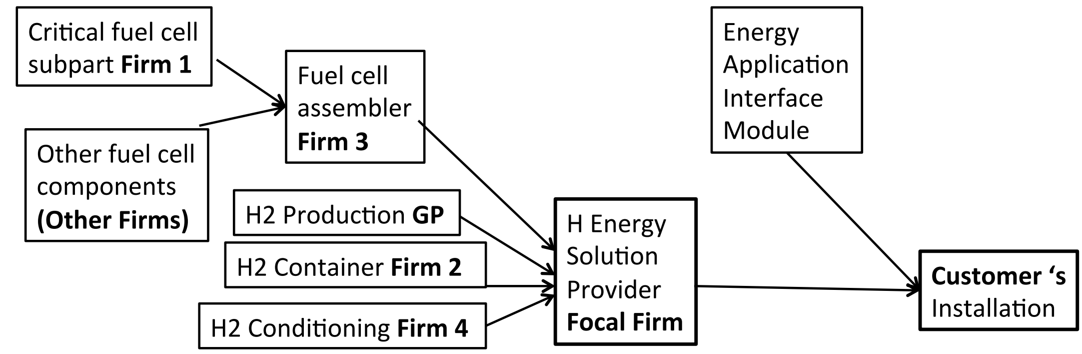


In five cases among the ten, the experiment generated an evolution of the actor involved, leading to an enlargement of the nascent ecosystem as shown in the different representations in the table. Hence, Figure 4 above will evolve with the progressive emergence of the ecosystem.

Table 3 Evolution of the ecosystem resulting from the knowledge generated through the experiments

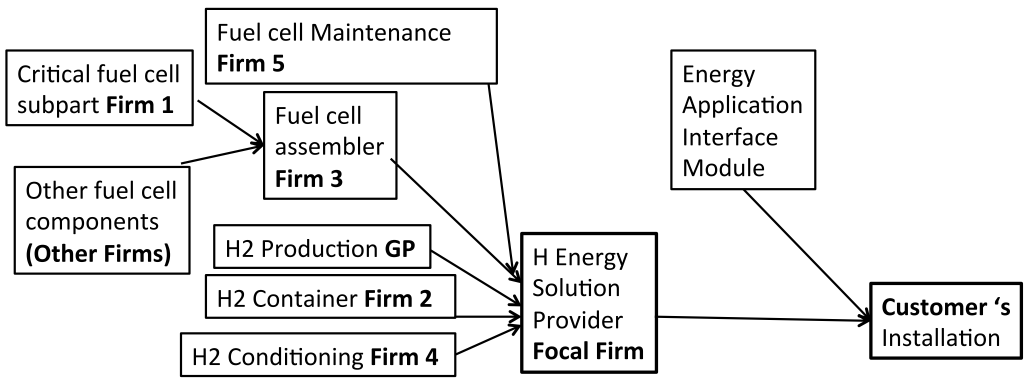
Experiments for the remote site market	Knowledge generated and actions undertaken
Experiment N°1: Delivering power to an antenna temporarily off the electrical grid. The customer is a small telco firm (Telco1)	- ***Market:*** identification of a new value proposition, the speed of deployment of the solution because the site is off grid temporarily. - ***Business model:*** a specific revenue model for a short duration of the solution delivery. - ***HES installation on the site:*** a component was developed to speed up the installation of the hydrogen containers on the site instead of building a pedestal in concrete as planned. - ***New actor to be involved:*** the provider of this component was integrated in the ecosystem.

Evolution N°1 of the ecosystem



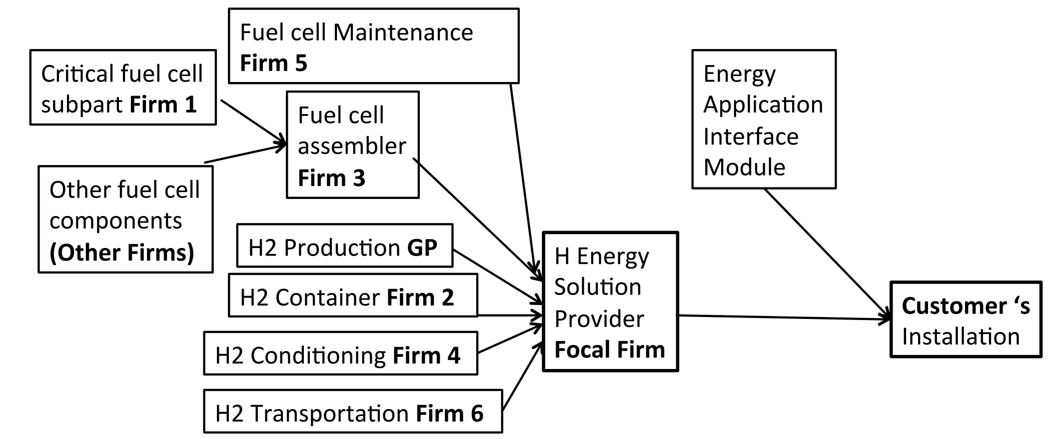
Experiment N°2: Delivering power to an antenna for a long period of time. The customer is the same as for the first experiment (Telco1).	- ***Performance and cost:*** integrated in the overall system, the fuel cell runs on a high regime leading to early wear of the membrane resulting in breakdown. A research program plan was launched to optimize the battery software targeting a reduction in membrane wear. - ***New actor to be involved:*** the risk of breakdown required the set up of a maintenance service operating on site to prevent or repair such breakdowns. Identification of players that could provide such services.

Evolution N°2 of the ecosystem

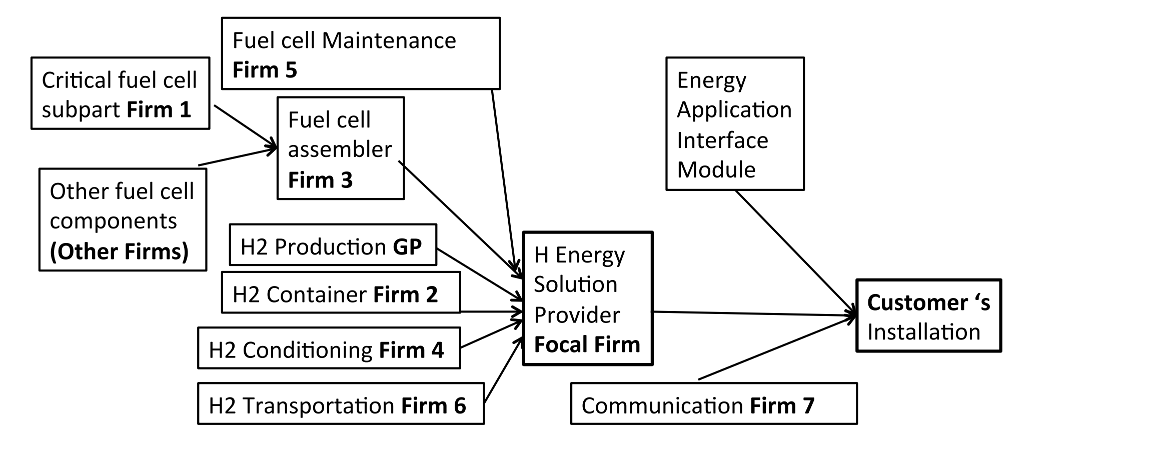


Experiment N°3: Delivering power to sensors needed to explore the potential wind energy generation of future sites. The customer is a small project manager in energy (Wind1)	- ***Market:*** identification of a new potential customer within the remote site market segment. - ***Performance:*** new range of power generation - ***H2 logistics:*** compact conditioning - ***New actor to be involved:*** the site required a specific transportation solution including a truck equipped with a crane.

Evolution N°3 of the ecosystem



Experiment N°4: Delivering power to sensors needed to explore the potential wind energy generation of future sites. The customer is overseas, thus the experiment is in an international context (Wind2)	- ***Operating conditions:*** The customer was located overseas. Hence, the experiment provides an opportunity to acquire knowledge on this new context. ***- New actor to be involved:*** The experiment relied on the international subsidiary of the focal firm and other international players.
Experiments N°5, N°6, N°7, N°8: Capitalization on past experiences with Telco1 for the same services.	- ***Business model:*** Interaction with the same customer in several situations allowed a more precise and accurate breakdown of the total cost of ownership for the customer, resulting in a new breakdown between the players. - ***Functional performance:*** the site was at a high altitude and low temperature, impacting the functional performance of the battery and requiring the adaptation of the hardware and the software.
Experiments N°9: Delivering power to billboards on segments of a highway that are not connected to the electrical grid. The customer is a big highway manager (highway).	- ***New market:*** powering the billboards on a highway when it crosses off-grid areas. - ***Performance:*** An incident occurred when operating the fuel cell - ***New actor to be involved:*** smoke emerged from the batteries during their operation and caused panic. The result was the identification of a player that has crisis management skills and communication towards the client, with users progressing towards the social acceptance of such innovation.
Evolution N°4 of the ecosystem	



Experiment N°10: Delivering power to an antenna for a major telecommunication operator (Big Telco)	- ***New market:*** providing a HES to a big established customer requires the development of knowledge on the way the value proposition has to be presented in order to be compliant with the purchasing procedures of such firms, for example. - ***Functional Performance:*** considering the critical service to be provided, this customer required that a remote control for the fuel cell was developed.

3.4 Types of knowledge generated by the Complete Solution Experiments

In the following, the knowledge generated by the ten experiments is summarized around four domains: the context of use impacting operation and performance, the actual operating costs, the performances valued by the customer and the overall service delivery.

Knowledge about the context of uses impacting operation and performance.

CSE enables the validation of the different components of the overall solution. Hence, it enables identification of the key factors that limit the overall performance of the solution either technically or economically, and enables them to be shared with all the contributors. As a consequence, the contributors focus on these issues and plan actions to improve the overall performance of the solution. Furthermore, the experiments enable trade-offs between these actions.

The operation of CSE revealed that the overall service performance was far below what was forecasted. As a consequence, several actions were undertaken by the different players involved: improving the membrane of the fuel cell, modifying the software monitoring the fuel cell, developing an integration module between the fuel cell and the customer applications that use the energy produced. In parallel, a test protocol was elaborated, incorporating the operating fuel cell environment parameters that impact the performance of the overall solution and could not be identified previously. While the previous steps led to the optimization of the subsets separately, the CSE provide important information for adjusting the subsets to their interactions in a real context of use.

Knowledge about the actual operating costs

The experiments revealed that, in real operating conditions, the lifetime of the membrane, an expensive component, was shorter than the assumptions made in the business plan and the hydrogen consumption was higher for a certain level of electrical power supplied. Here too, these performances could not have been evidenced if each component was optimized separately. Regarding the membrane, either the supplier develops another type of membrane with greater durability or the maintenance service provider replaces the membrane more frequently than was originally recommended. The experiment enables an assessment of the cost/benefit balance of each option. The CSE enables the transformation of the assumptions that affect the operating costs (hydrogen consumption, replacement frequency of consumables, unit costs of components, etc.) into validated knowledge, thus refining the business plan and leading to suggestions for improvement for some players.

Knowledge about the overall service delivery

Experimenting the solution with real customers in a real context evidenced critical issues such as its implementation on site. The fuel cell was originally designed to be placed in a shelter and gas cylinders placed in a concrete slab. The visit of actual sites where the solution was supposed to be implemented revealed that it was not possible to have such an infrastructure in remote locations. Several options were explored, including the adaptation of the solution to outdoor conditions. Their assessment and comparison of several criteria led to the choice of the integration of two subsets (the battery and gas bottles) in a unique container that can be placed directly on the ground outside. Here again, this solution would not have been identified if each partner addressed the issue on its own.

Knowledge about the performances valued by the customer

The experiments revealed that customers valued the speed of deployment of the solution on site. This was particularly critical in the specific market segment of transitional supply of energy to telecom antennas (while waiting for a connection to the grid, for example). Customers were ready to pay a premium for this rapidly available and temporary service. The business model needed to be adapted consequently. Another feature was valued by customers: remote startup and monitoring for specific operating conditions.
The experiments thus led to the identification of adaptations of the solution that could provide the customer with a more valuable solution.

Capitalization on the knowledge acquired.

As mentioned in the method section, the focal firm of the emergent ecosystem developed a management tool in order to capitalize on the feedback from the experiments. This tool was based on one configuration of the business model for the overall offer. It helped assess the different options considered when a problem was revealed and thus contributed to better steering of the actions undertaken. The focal firm synthesized and communicated the results of the different experiments to the contributors so that each one could infer the potential impact on its business. This communication about the progressive transformation of the assumptions into validated knowledge and the updates that followed the experiments contributed to building trust between partners. It was a strong motivation of the HE ecosystem coordinator at the focal firm with whom we had several meetings. Below are some verbatim extracts selected from these meetings:

> "We need to be realistic considering the uncertainty associated with this innovation. For that reason we have to gather information, analyze several options that have to be kept open. We have to be flexible, be aware of the weak signals."
> "We have to build and share a vision and develop sensemaking. The risk is that we do not consider the interests of the other stakeholders. We must beware not to reduce the vision to our financial and operational objectives."
> "We have to build trust with our partners not conflicts based on our strength and central position."
> "We have to set up an organization in which decisions can be taken rapidly by the relevant persons. Rules have to be explicit."
> "We must develop a sense of ownership for all the players involved."
> "We must make the assumptions and the behaviors that make the vision visible to all."

The observation of the actual performance of the various contributors eventually led to a readjustment of the distribution of revenue between them or the involvement of other companies to deliver a subsystem that was previously missing (transportation company equipped with specific transport vehicles, etc.).
Finally, these experiments with a complete solution in real situations with real customers generated sufficient knowledge for the focal firm to engage in negotiations with the public authority about the adaptation of the regulations and the design of specific incentives to encourage customers to adopt this form of energy.

4 Discussion – Conclusion

Our objective in this research is to understand the emergence phase of innovation ecosystems because, as mentioned in the literature review section, research on innovation ecosystems has seldom studied their emergence and specifically what processes and tools support it. We propose to qualify an ecosystem as emergent when the perimeter of the overall offer is not stabilized, the contributors to this offer are not all identified, and the rules between the contributors are still not entirely defined. Within this definition, many uncertainties therefore remain. Proceeding by analogy with innovation development processes, we relied on the literature on new product development and argued that experimentation that reduces uncertainties and supports knowledge creation in such processes (Thomke, 2003) may also play a role in the emergence and development of an innovation ecosystem.
Therefore, based on a framework resulting from the literature review and combining the literature on innovation ecosystems and innovation development processes, we analyzed the experiments performed within a nascent managed innovation ecosystem by the focal firm and its partners to reduce the uncertainties related to the global offer.
We highlighted the common characteristics that these experiments share and designated them as *Complete Solution Experiments (CSE)*. We showed to what extent the experiments resulted in a progressive evolution of the nascent ecosystem by identifying missing players for the delivery of an overall service valued by a customer. Moreover, we identified the types of knowledge generated by these experiments.
Below we will discuss these results, highlighting three contributions made by this research: the characterization of the CSE, its role in the emergence of an innovation ecosystem, and the types of knowledge generated.

Our first contribution is to specify the CSE enabling the generation of knowledge that will reduce the uncertainties associated with the emergence of the innovation ecosystem.
CSE involves all the players required to deliver and operate a complete solution (either components or complements providers, according to Adner and Kapoor's (2010) terminology). More specifically it involves real customers using the innovation in real conditions over a significant period of time in order to assess its overall technical and economic performances and to perceive its effective value. Hence this experiment requires a reliance, on one hand, on a previous identification of the market segments to be targeted even though it is far from being frozen, and on the other, on already developed and tested subsystems (components and complements). Thus, the experiment is highly refined in order to convince the customer to take part in this experimentation and switch from their current solution to this one, even for a temporary period. Last but not least, customers pay a price close to that targeted with the commercial offer although industrialization is far from being completed. Components and complements are representative of an industrial offer even though the experiment will generate information that will lead, in some cases, to the redesign of these elements. Finally, a critical characteristic of the CSE is that it contributes to the building and sharing of a common vision among the partners in the emergent ecosystem. Thus we argue that the way this vision is shared is of paramount importance, especially when there is a focal firm that monitors the CSE. The test protocol used to measure the performance parameters and the economic model, for example, are crucial elements that need to be specified upfront even though they will be progressively refined as the experiments go on (Probert el al. 1999). The CSE helps to build trust between the members: all the players who commit to the experiment know upfront how the data generated will be exploited and shared and are assured that they will get validated information.
These characteristics are summed up in table N°4 below.

Table 4 Characteristics of the Complete Solution Experiment

Dimensions of the experiment	Characteristics of the Complete Solution Experiment
Timing in the process	After an analysis of the market segments, and after the validation of main subsystems
Players involved	All players required to deliver and operate a complete solution Real customers
Knowledge targeted	Various kinds of knowledge: about the value proposition and the technical and economic performance
	Shared information about the global performance of the overall offer and subsystems with a predefined protocol
Cost	Shared by the companies involved
Fidelity	Usage in real conditions
Refinement	High
Duration	Significant period of time (3 to 6 months)

We use the dimensions highlighted by Thomke (2003) regarding the prototypes used in the innovation development process (timing in the process, players involved, knowledge targeted, cost, fidelity, refinement, duration, etc.) to outline the specificities of CSE. CSE is far from the low-cost probe, rough and basic prototype described by Lynn, Morone and Paulson (1996). A minimum amount of refinement is necessary because CSE involves customers that will use the service in real conditions. Even though the CSE is based on advanced components and complements that are already designed and developed, it would be misleading to believe that the CSE is a pre-commercial product. The experiment is an evaluative and a generative prototype and it can result in the redesign of some parts and/or the integration of new players.

Through this characterization, we extend the work of MacMillan and McGrath (2009) who studied the transformation of assumptions into validated knowledge during the innovation process. These authors did not address the specific case of innovation requiring the emergence of new ecosystem. We argue that CSE play a critical role in the transformation at the ecosystem level.

We also complement the work of Rohrberk et al. (2013) by adding a framework to a "collaborative business field exploration process" specific to the case of systemic innovation. CSE complements the collaborative business modeling that they suggested to answer the crucial question of how the individual organization will profit from creating a market.

The second contribution underlines four critical types of knowledge generated by the CSE in order to address the risks associated with the innovation ecosystem. Below we will highlight these types of knowledge in correspondence with the types of risks emphasized by Adner (2006; 2012). (cf. Table N° 5).

Table 5 Risks and knowledge correspondence in the emergence of an innovation ecosystem

Knowledge generated by the Complete Solution Experiment	**Knowledge to develop in order to reduce uncertainties associated with the emergence of the innovation ecosystem**	**Risks associated with innovation ecosystem** (Adner, 2006; 2012)
- knowledge about the actual operating costs.	- knowledge about the technical and economic performance of the overall offer,	- initiative risks (associated with the innovation development process)
- knowledge about the performances valued by the customer.	- knowledge about the functional performance of the overall offer and the benefits for the customer	
- knowledge about the context of use of fuel cells impacting operation and performance	- knowledge about interdependencies between the different building blocks of the offer and their providers	- interdependence risks (or co-innovation risks associated with the uncertainties of coordinating complementary innovators)
- knowledge about the overall service delivery	- knowledge about the adoption of the offer by the customer and the eventual integration modules to add.	- integration risks (or adoption chain risks associated with the adoption process across the value chain)

First, we showed in the data section that the CSE serves to measure the overall technical and economic performances in real conditions and thus to test the assumptions made for each component or complement. This helps reduce what Adner (2006) identifies as initiative risks and generates what Moore (1996) describes as technical knowledge.

Second, because the results of the experiment are accessible to all contributors, this knowledge helps make trade-offs between options that would solve ongoing problems. It thus reduces what Adner (2012) identifies as co-innovation risk or interdependence risk. As well as the test protocol used by each player to measure the technical characteristics of its components, CSE requires a test protocol because the solution and its constituents involve unknown interdependencies. The experiment in real conditions serves to identify parameters as well as interdependencies between subsystems that may influence the characteristics of the overall solutions that had not been previously taken into account. It thus leads to an improvement in partial test protocols, the reliability of which players agree on.
Third, the CSE enables the identification of problems that prevent the players from delivering an overall solution to the final customer and on which they all agree. They then focus on resolving these problems jointly and in a timely manner in order to satisfy the customer and ensure a viable economic model. Because of their participation in the experiment, each contributor is concerned not only by the performance of its own product but also by the global performance of the overall solution, which is what is visible to the customer. It thus generates relational knowledge (Moore, 1996) and enables the behavior of the different contributors to be tested.
Fourth, the CSE enables a progressive definition of the ecosystem’s scope. Should some additional services be included or some interface components integrated so as to facilitate the usage of the new offer to the customer? CSE reveals potential evolutions regarding new members to involve in the innovation ecosystem. By involving real customers and providing them with a preindustrial solution operating in real conditions, CSE can also lead to modifications of the value proposition. Such experiments thus contribute to reducing the integration risk or adoption chain risk as identified by Adner (2006; 2012).

The third contribution concerns the role of such experimentation in the emergence of an innovation ecosystem.
We argue that this type of experiment enables the prototyping of the innovation ecosystem and as such plays a critical role in its emergence.
Indeed, as well as supporting the development of knowledge needed to design a systemic offer, the CSE supported the emergence of an ecosystem in the following three ways.
First, CSE enabled joint resolutions of the problems faced by the partners involved in the nascent ecosystem in providing an overall solution to a real client. Resolving the problems encountered resulted in a strengthening of their relationships and interdependencies and their willingness to commercialize the systemic offer. When some problems turned out to be difficult to solve, the CSE led the focal firm to look for other partners which could compete with the initially identified partners of the nascent ecosystem.
Second, these experiments led to the enrollment of new actors able to deliver complementary services or modules. The nascent ecosystem was thus enlarged to encompass new contributors which were needed for the delivery of an overall solution. This progressive adaptation led to a stabilization of the perimeter of the offer as well as the innovation ecosystem.
Third, the partners willing to go further in terms of commercialization could mobilize the information gathered to define more precisely the rules that will govern their interdependencies.
The phenomenon highlighted between the partners involved in this nascent ecosystem and the joint experiment they took part into can be compared to a phenomenon analyzed by researchers focusing on evolutions of institutional fields. Lawrence, Hardy and Pillips (2002) showed that proto-institutions (composed of actors sharing new practices, rules and technologies that transcend a particular collaborative relationship) may become new institutions if these practices and rules are more broadly adopted. They suggest that such

diffusion occurs when the members of this proto-institution are highly involved.

Another comparison can be made between the ecosystem experimentation and CSE that we characterized and the experimentation highlighted in the literature on new product development. We stress how ecosystem experimentation can be specific and different from innovation experimentation. Thomke (2003) and Brown (2008) list the following principles regarding innovation experimentation: (i) to undertake experiments early in the innovation process, (ii) to experiment frequently, (iii) to experiment quickly, and (v) to fail early and often.

By involving real customers in real conditions, the experiments performed in the emergence of the innovation ecosystem as characterized above rely on several validated elements which make them impossible to carry out very early. Furthermore, it is more difficult to manage failures when the experiment involves many players.

The managerial implication of our contributions refers to the importance of designing experiments to build the overall offer progressively, to share a vision among the contributors and to ensure that successive experiments provide the missing knowledge.

One limitation of our research is that it considers an ecosystem with a focal firm and does not encompass other types of ecosystems.

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