Replication of industrial ecosystems for sustainable biofuel production

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Abstract

The utilisation of organic waste and other organic by-products for biofuel production needs to build on industrial symbiosis. The first challenge is to make such a symbiosis work as it involves setting up a complex system of input supplying and output using firms. Moreover, this is not enough. Due to the distributed character of biomass production, mass production of biofuels faces challenges when ensuring feasibility and sustainability of the produced fuel. At the same time, the need for adaptation of biofuel production to local conditions makes each biofuel production system unique and difficult to replicate in other locations. The distributed logic of biofuel production based on local industrial symbiosis is still a highly attractive business: biomass exists everywhere, as well as energy demand. However, the supply of biofuels does not automatically guarantee that there will be a demand for it. Current challenges of the concept are uncertainty and the need to consider multiple stakeholders' business and interests in order to adjust biofuel production to local conditions and ensure the stable consumption of the fuel.

In this paper we propose a framework for replicating industrial ecosystems for biogas production. This framework includes the systemic perspective on biogas industry, adaptation and collaboration mechanisms required for cooperating with the relevant stakeholders, the processes of functional modularisation and replication of the biogas production ecosystems. This generalised framework is expected to be relevant for any local biofuel production industry. The proposed replication approach is able to increase feasibility of distributed biofuel production while ensuring it environmental sustainability through the economies of repetition. With such approach biofuel industry can decrease uncertainty and increase knowledge and expertise part of the offering. In general, the proposed framework promotes decentralisation, collaborative way of working, and open innovation within biofuel and green energy industry. The research of a biogas production ecosystem is in the focus of this paper, however the overall logic proposed in this paper is considered to be applicable to the biofuel industry in general.

Keywords: biogas, replication, industrial ecosystem, functional modularisation, economies of repetition.

1. Introduction

The idea of material and energy round-put implied by the notion of industrial symbiosis (Allenby and Cooper, 1994; Baldwin *et al.*, 2004; Benyus, 1997; Chertow, 2000; Cote and Cohen-Rosenthal, 1998; Ehrenfeld, 2000; Geng and Cote, 2002; Graedel, 1996; Jelinski *et al.*, 1992; Ring, 1997; Templet, 2004; Wallner, 1999) has a tight connection to biofuel production. The reason for that is the fact that sustainability of biofuel is bounded by the properties of the biomass utilised for fuel production and the proximity of the biomass production unit to the biofuel production unit and biofuel consumption. Biomass has a lower energy content compared to fossil fuels, higher availability and therefore shorter distribution distances are more appropriate for its transportation (Gustafsson et al., 2011). The fuel produced from waste and by-product flows of nearby industries is more sustainable compared to fuel produced from, for example, food crops that are specially grown for that. Also, certain by-products of fuel production such as digestate from biogas production or nutrient mass from bioethanol production can be utilised in farming, replacing synthetic fertilisers or imported animal feed respectively. Thus production of renewable biofuel can be combined with effective cycling of nutrients.

The benefits of producing biofuels locally and according to the principles of industrial symbiosis are not only connected to ecological sustainability. Economical sustainability, i.e. feasibility of biofuel production can also be improved by connecting various by-flows into a working industrial ecosystem. Thereby several benefits can be achieved, such as savings on biomass production, capitalisation on by-products of fuel production and decreasing of transportation costs. The attempts to structure the biofuel industry in the manner similar to fossil fuels, i.e. by establishing a straightforward value chain, trying to gain economy of scale in order to make transportation of biomass and biofuel feasible even on longer distances, severely undermines the idea of 'green' fuels and shifts the environmental burden from one location to another (Mirata et al., 2005). As a result, the there is a high possibility for facing the same challenges as fossil fuel industry does: competition for resources, big fossil fuel share in transportation involved into production, and unfair exploitation of natural resources in certain regions to be used elsewhere.

Biofuel production within industrial ecosystems is local, which means shorter transportation radius, local production and local use. However, despite the sustainability benefits of such production mode, another set of challenges arise. These challenges are relevant for distributed production mode in general: high business uncertainty, especially in terms of investments, need for adaptation and setting up a complex system of firms supplying inputs to and using outputs from the system in every new location relative to the size of the investment. At the same time the distributed logic of biofuel production based on local industrial symbiosis is a highly attractive business: biomass exists everywhere, as well as energy demand. Moreover, both tend to be of comparable scale, which makes the ecosystems well balanced. For example, in a bigger city, where there is significant amount of organic waste, sewage sludge, etc., there is also a higher need for e.g. traffic fuel. In a rural area, where the biomass is mainly coming from fields and animals, the demand for energy is lower, respectively. However, even if a correlation between the biomass production and potential for biofuel consumption exists, this does not imply that the demand for biofuel will follow when the supply is established. The commitment of the potential fuel consumers is to be built just as of any other relevant business actors.

As opposed to the economies of scale obtained in fossil fuel production, such distributed mode of producing biofuels can use what has been called "economies of repetition" (Davies and Brady, 2000), meaning that though ecosystems for biofuel production will be 'tailored' for each location, the knowledge, both technical and business, required for replicating them can be 'reused' from project to project. Thus a biofuel producer can achieve costs savings, feasibility of biofuel production and at the same time maintain high sustainability of the produced fuel in all three dimensions: ecological, economic and social. These benefits include, for example, the increased share of renewable resources in the region, decreased waste generation and pollution, added value to local material flows (Johansson et al., 2005, Mirata et al., 2005).

Current challenges of the concept are uncertainty and the need to consider multiple stakeholders' business and interests in order to adjust biofuel production to local conditions. The capability to do so is directly connected to the notion of open or boundary-spanning business models (Chesbrough, 2006, Chesbrough, 2007, Wikström et al., 2011). In order to organise symbiotic relationships among various actors within a region, it is crucial to understand that these actors are usually already well-established and operating businesses in their own specific sectors with their own business logic and value chains. The involvement into an industrial ecosystem for biofuel production may be outside the vertical scope of their ordinary value chain if, for example, they are supplying a by-product or waste for biofuel production. Moreover, these business actors are often unaccustomed to working in a system (Gustafsson et al., 2011), since they operate in disconnected sectors and industries. The physical proximity of such business actors, i.e. operation within one community or region, is able to make their cooperation easier to establish due to possible personal networking, however does not abolish the fact that they lack capabilities to cooperate within an ecosystem for biofuel production in an industrial sense. The ability to connect those actors and understand how involvement into an industrial ecosystem can benefit their main business is the core for the boundary-spanning business models that are required for sustainable biofuel production.

The requirement for such business integration expands the need of establishing an industrial ecosystem from a purely technical perspective to the one with wider scope, i.e. establishment of a business or even social ecosystem that would make such sustainable cooperation function in reality. In this paper we treat ecosystems in a more inclusive way. By that we mean that industrial ecosystems should not only be sustainable from environmental perspective due to material and energy cycling, but also economically sustainable due to the business resilience of such systems. Recently the business research has focused on the importance of and opportunities provided by considering the business ecosystem around products and business models. Thus, Amit and Zott (2012) propose that a company can successfully innovate its business model by taking a systemic view, i.e. in the context of networks and ecosystems it operates within, instead of making isolated choices. In line with that, Tsvetkova et al. (2012) stress the need for a holistic approach when planning and developing the business side of industrial ecosystems. The need for having inclusive and cooperative business models is naturally relevant for industrial ecosystems, where the stakeholder integration is the pre-requisite for the whole existence of symbiotic relationships (Tsvetkova et al., 2012). However, such dependence on the context and on the corresponding stakeholders forming the ecosystem around a business or a product is also relevant for many other industries, which are not so much dependent on flow cycling, including ICT, consumer goods, and many others (Chesbrough, 2010; Amit and Zott, 2012).

Local conditions vary, making each biofuel ecosystem more or less unique. Speaking about the biogas industry, while the technology can remain similar for any biogas plant, the biomass input is able to affect the whole business model of a biogas producer, by putting limitations on the products use, or changing the earning logic from a waste treatment company to a traffic fuel producer. In a similar way the potential demand conditions affect the offering as such: sales of biogas as a traffic fuel or use of biogas for combined heat and power production define the distribution needs, potential customers, need to collaborate with vehicle sellers in the former case or energy companies in the latter case, and so forth. The enforcement of the same production and consumption patterns regardless of the local conditions, such as type of available biomass, potential energy demand, and business environment, is neither reasonable nor possible in biofuel production industry. Ignoring this fact often leads to the situation when small-scale biofuel production companies are unable to expand their business. Modularity in the development of industrial ecosystems for fuel production would make it possible to achieve the economies of repetition (Davies and Brady, 2000) and make the business feasible and sustainable as outlined earlier. Modularity can be reached through standardising approaches to collaborating with actors in various locations, in technology, contractual issues, etc. Replication through functional modularisation and mass customisation of biofuel production ecosystems are proposed in this paper as the solution to the outlined challenges. In this paper we present a framework for replicating industrial ecosystems for biogas production. This framework includes the systemic perspective on the industry, adaptation and collaboration mechanisms required for cooperating with the relevant stakeholders, the processes of functional modularisation and replication of the biogas production ecosystems as well as biofuel production ecosystems in general.

2. Theory

2.1. Replication

The success of 20th century industrial activity is undoubtedly at least partly a result of the conscious pursuit for economies of scale (Chandler, 1990). The simple logic that the more you make of something, the cheaper you can make it, or differently put, the more standardised the things we make the cheaper they become (because we can make more of similar things), revolutionised industrial production.

Capital goods, in turn, such as raw material process plants, have relied on a logic where characteristics of raw materials are explored and the capacity of the plants is set to meet the expected demand (at a certain point in time). As a result, the outcomes are customised designs and more or less unique projects. This is not a problem for large plants, but for smaller it is likely to be as the revenues cannot bear the cost of customisation. For companies delivering small capital goods such an operating model becomes inefficient (Magnusson et al., 2005). Not everything has to be unique. Lampel and Mintzberg (1996: 21) express the central idea of this standpoint elegantly:

> *...customization and standardization do not define alternative models of strategic action but, rather, poles of a continuum of real-world strategies.*

Capital goods companies, too, strive to standardise their products and reuse their designs. As firms deliver more similar projects they can achieve so called “economies of repetition” putting in place organisational changes, routines and learning processes (Davies and Brady, 2000). As capital goods projects include much more than mere products (goods, hardware), a goal would be to be able to deliver entire “repeatable solutions” (Davies and Brady, 2000).

A pursuit of “economies of repetition” opens up an opportunity for replication, a strategy that is often associated with firms such as McDonald’s or IKEA entailing the creation and replication of a business format (Jonsson and Foss, 2011, Winter and Szulanski, 2001). Replication is, however, far more than the standardisation and exploitation of a business model. Winter and Szulanski (2001) argue that it is a specific type of strategy that, in addition to an exploitation regime, also involves a subtle exploration phase of business model development. They have identified four key elements of a replication strategy: knowledge transfer, the role of a central organisation, a template and the Arrow core (see also Jensen and Szulanski, 2007). The notion of the Arrow core refers to the ideal set of information to be transferred to a replicator. The relation between a template and the Arrow core resembles that between facts and theory (Winter and Szulanski, 2001).

While some technically rather complex technologies, such as semi-conductor manufacturing equipment need to be copied exactly to enable the execution of a replication strategy (MacDonald, 1998), other cases require a more adaptive approach. Jonsson and Foss (2011) found that IKEA’s success in replicating their business format to various international locations partly lies in the flexibility of their approach. The authors stress the organisational support for key elements like an on-going learning process, frequent modifications and local adaptation.

As Ruuska and Brady (2011) note, the replication literature is scarce on cases in which replication is (moderately) complex. They illustrate the difficulty of pursuing such a strategy in uncertain and complex investment projects such as the design and construction of renewable diesel refineries, where the underlying technology is still immature causing frequent design modification during the implementation phase. In the special case of complex products and systems (large-scale high-cost capital goods), Brady and Davies (2004) argue that at the core of repeatable solutions lies a base moving, “vanguard” project that triggers a process of project and organisational capability building. In their project capability building model the firm moves from the exploratory “project-led exploratory learning to business-led learning where the developed capabilities are exploited in repeated projects.

Lampel and Mintzberg (1996) have identified three areas in industrial production that can be standardised or customised: the product itself, the working processes and the transactions. In this paper we treat the two first through the lens of modularity. Transactions, in turn, lie at the core of business model design (Zott and Amit, 2007). However, in the case of biogas industries we need to consider the entire industrial ecosystem around the biogas production facility, rather than design and replication of a single firm’s business model. Instead, we have to consider transactions that span traditional firm boundaries and develop the business models and replication templates accordingly.

2.2. Modularity

The ability to replicate strongly builds on modularisation and mass-customisation. The idea of creating variety through modular production was presented more than 45 years ago (Starr, 1965) and was popularised by Joseph Pine in his influential book (Pine, 1992) and a series of co-authored articles in the 1990s (Pine, Victor and Boynton, 1993; Pine et al., 1995; Gilmore and Pine, 1997). The idea central to mass customisation is the pursuit of meeting specific customer requests at near mass-production efficiency (Pine et al., 1995). Mass-customisation can be seen as the production strategy or business concept evolving from a flexible, modular product and process design. A modular design, in turn, enables the configuration of modules and processes into customer-unique deliveries, which as a whole constitute the basis for successful mass-customisation.

Modularisation is performed through, first of all, identifying commonalities (Rutenberg, 1971) between product variants in a product family and, second, embodying them into modules. At the same time the need for variety should also be identified and embodied into alternative and interchangeable modules. Interfaces play a crucial role by allowing for interchangeable building blocks. Once identified the modules and their interfaces form the basis for a whole product family or, in other words, constitute a so called “product platform”.

Lampel and Mintzberg (1996) also show how modularity can be used to balance the two opposite forces of standardisation and customisation along a continuum of choices. They introduce a categorisation of five strategies between the two extremes. Based on where in a four-step value chain (design-fabrication-assembly-distribution) the product becomes customised, they differ between: pure standardisation, segmented standardisation (customisation in the distribution process), customised standardisation (in the assembly process), tailored customisation (in fabrication) and pure customisation.

The use of modularity for mass customisation is able to reduce complexity of various systems through creating variety and utilisation of similarities (Hellström, 2005; Lampel and Mintzberg, 1996; Miller and Elgård, 1998). Industrial ecosystems, being complex systems comprised of material flows, businesses, regulations, etc. can benefit from applying this approach. Although the possible composition of an industrial ecosystem for biofuel production varies from location to location, this variance is limited from the functional perspective. For instance, there is a limited number of alternatives for biogas utilisation and for biomass supply. Thus, the functions in such an industrial ecosystem are more or less standard, while different businesses can serve these functions depending on the location.

Another benefit of modularity is that it can provide both flexibility and structure (Hellström and Wikström, 2005; Sanchez and Mahoney, 1996). In businesses that incline to mass customisation rather than mass production, flexibility in business model can be reached through defining interchangeable modules to be re-combined in order to fit any particular solution into the local conditions.

We further adopt a systems-based approach to industry classification (as opposed to activity-based approaches), which “defines a sector on the basis of similarity in needs to which firms collectively respond” (Dalziel, 2007: 1559). This view draws on modularity theory and sees sectors as hierarchical structures being built up from sets of sub-sectors, which, in turn, comprises sets of central and complementary firms (Dalziel, 2007). Hence, we divide the biogas industry (a special case of the biofuel industry) into a service sub-sector, comprising the energy company, and a manufacturing subsector. As central firms in the manufacturing subsector we see the reactor suppliers (systems integrators) and a wide range of subsystem a component suppliers. Among the complementary firms we find for example engineering firms, construction companies, farming businesses and inspection agencies.

2.3. Boundary-spanning business models

The concept of innovation ecosystems rises from the idea that innovating firms are dependent upon other innovators in the same sector, such as upstream component suppliers and downstream suppliers of complementary products or services (Adner and Kapoor, 2010). In order to establish industrial ecosystems, involving even larger number of actors, it is therefore absolutely required to consider other actors’ business models, understand them and be open for adjusting to them. This way the actors can be committed to be part of the ecosystem that is vital to the distributed mode of biofuel production.

Thus, standardisation needs to be in proper balance with flexibility in adapting to local variations in order to replicate biofuel business based on ecosystem view. The earning logic, the offering, the customer, and other elements of business models (Afuah and Tucci, 2001; Chesbrough and Rosenbaum, 2000; Linder and Cantrell, 2000; Osterwalder et al., 2005; Zott and Amit, 2008) may therefore be different for various locations. Therefore, the major capability in boundary-spanning business models is the ability to manage the complexity of the system and coordinate it efficiently.

Speaking about sustainability, not enough attention is paid to the opportunities provided by being part of a system larger than the traditional direct value chain of a company. Attempts to refine own business, production unit, or equipment have lead to significant technology and process improvements. However, the systemic view is often lost together those improvements (Ehrenfeld, 2008; Jackson, 2009), and such attempts lead to sub-optimisation of the system. Often, system benefits, i.e. the advantages of being part of a bigger system, are overlooked due to extremely internally-oriented business models, or are ignored in order to avoid the complexity and uncertainty associated with dealing with variety of actors that cannot be easily controlled. Moreover, many industries are characterised by established value chains and sets of actors, making it difficult to ‘span the boundaries’ of their traditional business models and allow for more cooperation with ‘unusual’ partners. For example, the involvement of farming into the bioenergy industry, though indirect, may prove to be challenging, because the involved business actors are not accustomed to working together in the field of traffic fuel production.

The need to have more open and inclusive business models has been discussed in the literature on open innovation and 'boundary-spanning' business models (Chesbrough, 2006; Chesbrough, 2010; Wikström et al., 2010). Such business models urge for deeply taking into consideration the businesses of relevant stakeholders such as customers, suppliers, and partners. By doing so it is possible to build a stronger network or ecosystem around a company's own business, generate system benefits, and thus have the business ecosystem as a competitive advantage.

In case of bioenergy the adoption of boundary-spanning business models means the transformation from the traditional linear value chain for fuel production to a ecosystem, where stakeholders are deeply integrated into the whole business logic. For example, fuel demand in such case can affect the bioenergy company's offering, the business models of biomass producers and other stakeholders need to be considered and attempts to connect to them are taken.

Through boundary-spanning business models the systemic perspective can be embedded into the businesses of various actors by attempting to find connections to other industries and value chains and being open to cooperating with various businesses. However, interfaces among industries and business actors that are unaccustomed to work together still need to be established. This connects back to modularity, which can allow for standardising various interfaces, when stakeholders' businesses are treated as modules in an ecosystem. Understanding of different ways to cooperate with the actors in the ecosystem is absolutely needed for replicating those systems in various locations.

The activity of understanding the relevant stakeholders' business models and attempting to connect to them may serve as a basis of developing collaboration mechanisms, which can be replicated from location to location and help in 'enrolling' actors with similar business models into the newly established ecosystems.

2.4. Collaboration mechanisms for establishing interfaces

Integration of various actors from farming, fuel production, distribution, transportation, energy production and many other sectors is a necessary and at the same time a difficult task. The product itself, i.e. biofuel, cannot integrate this system without creating bias in value and benefit distribution among the actors. There is a need for mechanisms that create intangible flows between the elements of an industrial ecosystem and make it beneficial for all the involved parties. This in turn will commit them to be the part of the system and provide their input. Such collaboration mechanisms would trigger and enhance cooperation between the actors in the biofuel business ecosystem.

The research on collaboration (Powell et al., 1996; Dyer, 1997), cooperation (Dyer and Singh, 1998; Gulati and Singh, 1998) and network governance (Jones et al., 1997) is, in essence, touching upon the same phenomenon of actors creating products and services "based on implicit and open-ended contracts to adapt to environmental contingencies and to coordinate and safeguard exchanges" (Jones *et al*., 1997). In this paper we focus on the ways collaboration can be reached through optimisation of boundary-spanning transactions (Zott and Amit, 2007) and through social mechanisms (Jones et al., 1997).

Cooperation required for establishing boundary-spanning business models can be triggered by collaboration mechanisms. Since biofuel business is a highly capital-intensive industry, the initial investments in new facilities and business establishing constitute major barrier for replicating the business in new locations. Moreover, as business conditions vary due to the nature of distributed energy production, the collaboration acquires temporary and localised character. Therefore, the repeated transactions highlighted by earlier writings on collaboration as the major aspect (Dyer, 1997, Jones et al., 1997, Schwab and Miner, 2008) becomes irrelevant for the context in focus.

Continuing the idea of modularity in developing industrial ecosystems for biogas production, interfaces among the modules play a crucial role. Taking businesses of the involved actors as modules, we are more interested in interactions between those modules, rather than within them. This is partly due to the fact that in complex systems the behaviour of any one module depends in only an aggregate way on the behaviour of the other modules (Simon, 1962), or, to put it simple, business actors within an industrial ecosystem may be rather independent and can only be influenced if other actors make changes in their general functions in the ecosystem (Tsvetkova and Gustafsson, 2012). The other reason for focusing on the interfaces between modules is their inexistence. In this paper we focus on collaboration mechanisms that help to establish the interfaces among various actors and make the ecosystems function. The key to those mechanisms is the reasonable value redistribution and incentivizing (Turner and Simister, 2001) of the actors to be part of the ecosystems.

Development of collaboration mechanisms can be done by considering the stakeholders' operational and capital cost structures, industry logics, and business models. Then, the connections between them can be established by various collaboration mechanisms. Although these mechanisms would vary from location to location, certain contractual and incentivizing models may be developed and further applied in other location with minor adjustments. This would allow replicating sustainable solutions based on industrial symbiosis without the need for high adjustment costs. Thus economies of repetition (Davies and Brady, 2000; Hellström, 2005) and consequently cost saving could be reached.

3. Methods

3.1. Research context and approach

The research has been carried out during the period 2011-2012. The researchers directly participated in the development of an ecosystem for biogas production and utilisation system together with the relevant stakeholders. The aim of this study was to design the business solution that would be sustainable and feasible in the long term. For that, the ecosystem was mapped, business models of the relevant stakeholders were analysed, and the collaboration mechanisms were designed based on this data. The second task was to develop the replication approach, which would allow for developing ecosystems for biogas production and utilisation in other contexts. This paper presents the main findings of this research, as well as the framework for ecosystem replication that has been developed.

Clinical approach (Schein, 1993) and design science approach (Romme, 2003) were in the core of the research methodology. Clinical research implies direct participation in solving research object's challenges, or in other words engaging in research activities, which are based on the needs of organisations. The benefit of such approach is in better accessibility of the research objects: in many situations the most relevant and critical areas of social life, including business, are closed to 'outsiders' due to sensitivity of information and context. Such participative approach not only allows for accessing sensitive contexts, but also ensures commitment of research participants to co-create valid knowledge (Schein, 1993). In such case the validity and, what is important, relevance of the produced knowledge are ensured by studying social systems 'as they react to experimental manipulation' (Clark, 1980). This means that the research interest lays not so much in the current situation, but in the way it can be improved.

While the descriptive and analytic nature of traditional management science helps to explain existing and emerging phenomena, it cannot account for qualitative novelty (Bunge, 1979; Ziman, 2000; Romme, 2003). Design science approach, on the contrast, uses ideal target systems when defining the initial situation and pushes people towards thinking *how* system could be made to work (Romme, 2003), and therefore can contribute to the needs of clinical research in developing solutions to the problems and at the same time answer the ‘how to’ question by being directly involved into the development of the studied phenomena. According to Romme (2003), design approach draws on purposes and ideal solutions, systems thinking, and limited information. Design aims at changing the existing situations into desired ones (Romme, 2003), and is based on pragmatism as the underlying epistemological notion.

3.2. The ‘biogas for traffic’ case

The ecosystem in focus of this study is based on local biogas production and utilisation as a traffic fuel primarily in public transportation and by other high-volume users. The main actors in the system and the material and energy flows between them are visualised in Figure 1. Other actors, not included in the flowchart, include for example financing agencies, construction companies, various permitting, legislative bodies, and authorities. However, we want to underline that all of the actors are crucial as they are part of a system that can fail when even one element does not function properly.

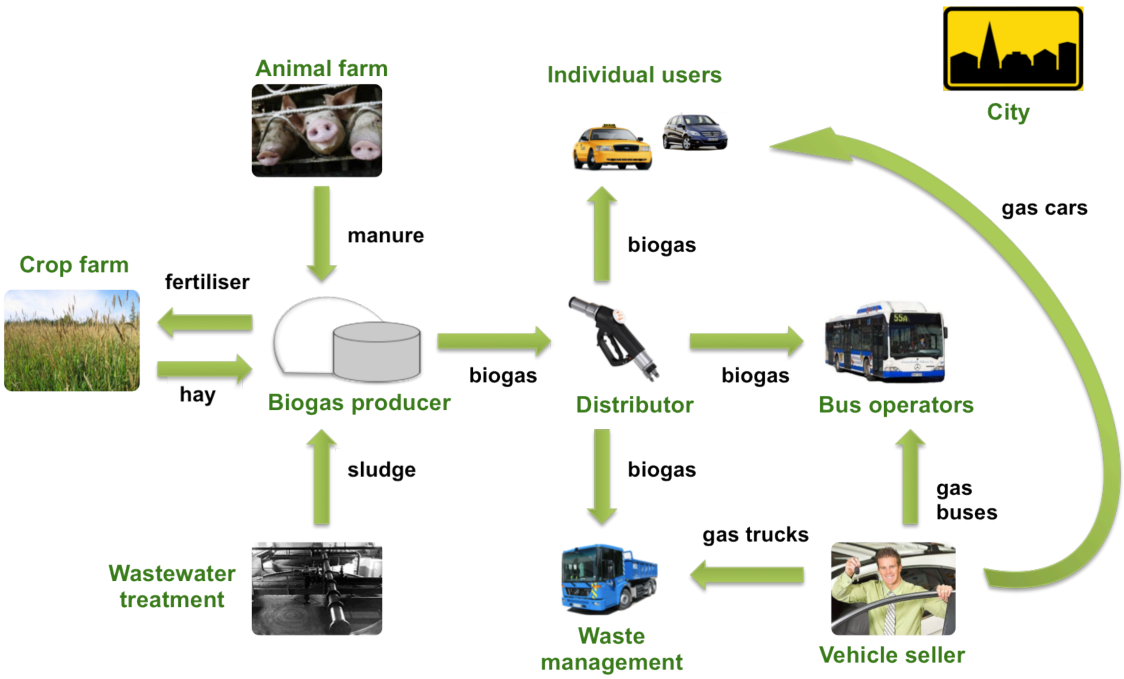

Figure 1. The ecosystem for biogas production and utilisation

The ecosystem presented in Figure 1 has been developed in a long process of identifying the critical actors, and adjusting the system to the specific location. For example, the process of utilising sewage sludge for biogas production has existed in the area, and thus was the first ready module for developing the ecosystem. However, further research showed that when certain volumes of biogas production are exceeded, other modules bearing the same function of biomass production would be required. This could be, for example, crop or animal farming that supply grasses and manure respectively.

The distinguishing feature of the process for designing the focal ecosystem is that consumption is approached the same way as downstream value chain. This is due to the fact that investments into biogas distribution system are high, and unless the consumption is ensured from the start, the uncertainty in making the investments is too high. Therefore it was decided to focus on big potential consumers of the biofuel and connect to their business models in order to make them interested in participating in the whole ecosystems as biogas users.

4. Results

4.1. Challenges in developing industrial ecosystems

Challenges that are relevant for distributed production mode in general include high business uncertainty, need for adaptation to local conditions and setting up a complex ecosystems consisting of firms supplying inputs to and using outputs from the system.

In the focal case the major uncertainty concerned investments, because certain elements of the ecosystem did not exist: e.g. distribution infrastructure, vehicles that utilise biogas required significant investments from respective actors. The benefits of and incentives for engaging into such an ecosystem need to be visible for the relevant stakeholders. Here we mean not so much the environmental benefits, but rather the implications on the stakeholders' business models: earnings, costs, etc. Considering that constellations of ecosystems, even if they are still based on biogas production, will vary from location to location, the investment needs and incentives for them will also vary.

Another relevant challenge is to ensure cooperation between the stakeholders in such an ecosystem. For example, a prerequisite for utilisation of biogas as traffic fuel is that the proper quality and quantity of the biogas is available for the users. The biogas needs to be upgraded in order to fulfil the equipment requirements, which is more of a technical issue. The quantity of biogas directly depends on biomass supplied for its production. The agreement with biomass suppliers, such as waste management companies, food production companies, or farms, cannot be reached by technical integration and includes social and economical reasoning. i.e. establishment of a certain interface. Since such suppliers vary from location to location, it is a serious effort to ensure they are committed to be a part of a system for biogas production.

The uncertainty and complexities outlined above can be managed through mass customisation and functional modularisation. It is required to define the standard and variable elements in the ecosystem and develop modules and interfaces according to this information. This would allow for replicating not only the physical units required for biogas production, distribution and utilisation, but also the relevant knowledge on business models, collaboration mechanisms and commitment building among the actors.

4.2. Framework for replicating industrial ecosystems

The replication framework presented further is drawn on the functional modularisation approach. This means that the main characteristic by which modules are distinguished is the function they serve within the ecosystem. The functions in the focal ecosystem included, for example, biomass supply, biofuel production, biofuel consumption, support in consumption, biofuel distribution, by-flow utilisation, and permitting. Various business actors can serve as modules for the outlined functions. For instance, biomass supply in the ecosystem can be performed by waste management companies delivering organic waste, wastewater treatment companies delivering sewage sludge, or farms delivering grasses, crops, and manure. Similarly, biogas use can be done by vehicle users, such as bus operators, or industrial factories close to biogas production plant. What is unchanged is the fact that the biogas needs to be consumed and that there should be enough biomass to cover the production needs.

In each location the possibility of using various modules is different. But as a system integrator a biogas producer or distributor can have standardised: modules, i.e. what are the opportunities for various businesses to cooperate with, and interfaces between modules based on collaboration mechanisms with potential stakeholders. In this section we outline the way replication can be done based on this approach.

Replication of industrial ecosystems for biofuel production can be done in the following three steps:

- **Step 1. Outlining the desired ecosystem and functions within it**
  This step includes the exploration of opportunities in the target area. First of all, the relevant existing actors are mapped. For example, in the focal case the biogas production plant already existed as well as the biomass supplier – wastewater treatment plant supplying sewage sludge. Also, the need for biofuel is to be considered at this stage. In the focal case the location was characterised by the need for public transportation, because it was an urban area. By understanding the local conditions the desired constellation of the industrial ecosystem can be outlined, as schematically presented in Figure 1.

  When the desired system is defined the functions within it need to be mapped. According to the functions, such as biogas consumption, support in consumption, or biomass production, the required business actors need to be defined. At his point these actors act as modules in the developed ecosystem, where they serve certain functions. Thus, the previous knowledge of the system integrator on which businesses can serve certain functions can be utilised for mapping the potential stakeholders in the system.

  Definition of which businesses need to be included into the ecosystem is done also on the basis of material flow mapping, which includes environmental sustainability dimension into the ecosystem design process. For example, if it is clear that in the target location certain organic waste flows are excessive, they might be considered first of all as the inputs for biofuel production. This increases environmental sustainability of the whole solution as well as it may increase its feasibility if the biomass is provided at low or no cost.

- **Step 2. Understanding business models of individual stakeholders**
  When the required modules, i.e. businesses, are defined, the next step is to understand their business models. This step needs to be guided by the idea of boundary-spanning business models, which can interconnect tightly for the increased value creation. Thus, the system integrator is to understand the relevant stakeholders' business models in order to be able to make such inter-linkages. The following elements are crucial to be defined for the potential actors in the ecosystem:

  – Business model: earning logic, costs structure, customer, organisation, etc.
  – Potential benefit from the biofuel ecosystem
  – Input required from the actors into the ecosystem, i.e. their function
  – Challenges associated to their involvement (e.g. risks, investments needed, etc.)

  Wherever an ecosystem for biogas production is developed, for example, within the same country, a biogas producer or distributor can be aware of a farm's business model and the way it can be involved into an ecosystem. This is achieved through understanding that fuel industry is not the main business for a farm, analysing what the farm's business model is, including cost structure, challenges, and what benefits they could get from taking part in the ecosystem. Then an ecosystem integrator can approach the farm with a pre-defined and tested way of working, for example, by offering fertilisation service in return for biomass.

- **Step 3. Collaboration mechanisms**

  The next step is based on the information received in the previous steps and constitutes the actual business planning. The aim is to define how interfaces between different modules need to be established in the target context through collaboration mechanisms. Similarly to defining modules, the system integrator is able to utilise the previously generated knowledge on collaboration mechanisms that can be used for cooperating with various types of stakeholders.

> As an example, a certain pricing model can be used as a collaboration mechanism to engage potential biofuel users into the ecosystem. The concrete solution to establishing this collaboration mechanism is, for example, offering of long-term fixed-price for large users of biogas. It goes in line with both parties' business models and is mutually beneficial since it provides the basis for setting up the system by dividing the burden of investment on many stakeholders and allows for selling the remainder of the gas produced at a premium to customers that are not strategic (for example individual consumers).

The proposed framework demonstrates how knowledge can be reused from location to location, and how replication can be done based on that.

5. Discussion and conclusions

The opportunity to establish biofuel business on a large scale through replicating the ecosystems around it is attractive from economical, environmental, and social perspectives. However, treating physical units in a modular way is not enough – business and social elements need to be replicable as well. The inclusion of such heterogeneous elements into business planning make it challenging to design and replicate in other locations. However, this can be done by applying functional modularisation, where the modules are defined according to the functions they serve in the ecosystem and interfaces are driven by collaboration mechanisms. This approach allows including the complex business planning and cooperation elements, otherwise ignored when ecosystems are designed purely from material flow perspective.

The urge for understanding the relevant stakeholders' business models, needs and challenges associated with their participation in the ecosystem is the concrete contribution to the way boundary-spanning business models can be realised (Wikström et al., 2011). The collaboration mechanisms in this case play the role of triggers for interlocking with other business models. This is especially relevant for integrating industrial ecosystems, where the lack of one actor may undermine the resilience of the whole system (Gustafsson et al., 2011). This is the reason why early planning of how actors need to be committed plays such a significant role.

The modularisation approach allows for managing the complexity associated with industrial ecosystems by re-using and re-applying the knowledge about the functional modules, i.e. businesses, and interfaces between them. It needs to be underlined, that even though the pre-defined modules and collaboration mechanisms to build the interfaces can be re-used, the learning process occurs constantly and new and new alternatives for modules or interfaces can be developed during constant replication, i.e. reapplication of knowledge. This is the way organisational learning can benefit to developing the core capability of the system integrator: being flexible along with standardising (Lampel and Mintzberg, 1996).

It needs to be underlined that depending on which actor takes the role of the system integrator, the possibility to replicate the ecosystems may be bounded by certain challenges. A biogas producer, for example, may lack the necessary knowledge to establish an ecosystem in which biogas would be used for local traffic, and thus has limited opportunities to expand the business. A biogas distributor in such case has a more central and decisive role, and thus is a more appropriate system integrator. Depending on the position of the system integrator in a value chain it may need to develop new capabilities in order to understand the whole ecosystem around the biofuel and to be able to establish collaboration with other actors that are necessary. The motivation for being a system integrator is thus to be able to expand the biofuel business, which may be limited physically by local biomass availability and biofuel need.

It is a common case when a municipality becomes the leader of a biofuel project to introduce ‘green energy’ in the area. In such case all the involved actors may still remain unaware of the system perspective and uninterested of spreading the business concept elsewhere. At the same time, the municipality, as a non-business actor, is normally not interested in re-applying the knowledge in a new location. Certain knowledge can be still transferred to the actors attempting to develop a similar ecosystem, but the benefits of business replication would be eliminated.

The case discussed in the paper illustrates how open innovation and boundary-spanning business models are able to contribute to the overall industry sustainability by encouraging companies to engage into deeper relationships with various stakeholders and taking a systemic outlook on their business environment.

The proposed replication approach is able to increase feasibility of distributed biofuel production while ensuring its environmental sustainability through the economies of repetition. With such approach biofuel industry can decrease uncertainty and increase knowledge and expertise part of the offering. In general, the proposed framework promotes decentralisation, collaborative way of working, and open innovation within biofuel and green energy industry.

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