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## The emergence of doubly green chemistry, a narrative approach

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Using a narrative approach, we describe the emergence of the "doubly green chemistry" concept more as the product of a collective action in building a new sector, than an innovation breakthrough brought by individual actors. This action is initiated by the agricultural and agro-industrial firms that seek to substitute oil-based products by finding new uses of agricultural products. These actors have built "community productive patrimonies" by assembling knowledge bases and institutional resources. In order to mobilize their communities, they use the "rational myth" of plant cracking, later transformed into biorefinery by integrating the principles of green chemistry, to make the technological changes sustainable.

Green Chemistry, Green Economy, Biopolymers, Sustainable Development, Biorefinery, Rational Myth, Technological Expectations

What we call *Doubly Green Chemistry* (DGC in the remainder of the article) consists of all scientific and socioeconomic systems dedicated to developing alternative technologies for fossil fuels by using renewable raw materials from agriculture and forestry (Nieddu & Garnier 2008, Garnier, Kurek, Nieddu, 2008). These systems suggest a possible sectoral reorganization that is yet to be defined, but that would include dedicated crops and some of the energy, chemical and food industries (additives and animal feed). This article is one phase of a program which aims to describe the actors' efforts to create the economic space involved in this reorganization.<sup>1</sup> According to the accepted view [see Octave and Thomas (2009)], it

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<sup>1</sup> This phase will describe the economic environment of DGC researchers, as part of the ANR project focused on the role of the researcher in this process ("An Economic Approach to the Integration of socio-economic and technological dimensions in Doubly Green Chemistry Research

is the segment involved during the extraction, separation, or cracking of the biomass, and then its functionalization and formulation. This segment ends with the delivery of “intermediate agro-industrial products” (which the actors would like to be quite diverse, including fatty acids, modified starches, elastomers, fibers, resins, sugars, antibiotics, vitamins, polymers or monomers, ethyl esters, dextrans, surfactants, organic acids and alcohols).

These are “semi-products,” a term coined by Weil (in Le Masson, Weil, Hatchuel, 2006): products, some of whose parameters are validated while others remain open to exploration, which will have to successfully combine with other technologies in a wide variety of industries such as energy, cosmetics, metallurgy, paper industry, construction, pharmaceuticals, wood industry, pollution treatment and plastics. The need to base the new economic relations on shared knowledge, common tools and communities of actors from different backgrounds led us to examine the current dynamics in terms of forming *community productive patrimonies*.

## Why talk about Dubly Green Chemistry?

The term DGC refers to two concepts. One designates the origin of the raw materials, and equates green chemistry to *bio-based chemistry* (Colonna, 2006). The other refers to the need for the chemical industry, in response to industrial accidents and toxicity problems, to redefine itself in terms of its impact on the environment. During the 1990s, green chemistry was codified in 12 non-binding principles by Paul Anastas of the U.S. EPA, and institutionalized in Europe through binding directives such as the REACH Directive. Green chemistry seeks out the best possible compromises, given the state of knowledge and processes, to avoid toxicity and minimize the waste associated with traditional chemistry. While the 7th principle recommends that “A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable” (Anastas and Warner, 1998, p. 45), nothing guarantees that renewable carbon chemistry in place of petrochemical intermediates will meet the principles of green chemistry, or even be acceptable in terms of more general principles of sustainable development. What we call DGC is therefore more of a problem to be solved and a goal that an available solution.

## Incentives to embrace Doubly Green Chemistry

Complying with the principles of green chemistry is only one aspect of the issue of achieving sustainable technological change that this article seeks to address. Indeed, it is not enough to take note of changes in oil prices to derive alternative paths. While these changes seem to offer opportunities, this tells us nothing about the economic and technological alternatives that the actors may succeed in developing. The actors are required to drive change by making *ex ante* decisions in a context of heightened technological uncertainty. However (1) they are part of productive systems that offer them resources and response capabilities, but also limit the scope of possible actions, subject their actions to viability requirements (Amendola and Gaffard, 1992), and lead them to seek change along specific pathways. (2) One feature of firms undergoing rapid technological change is the

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Programs”).

existence of hypercompetition for materials and emerging technological alternatives (Larrue ode la Tournemine, 1991).<sup>2</sup> We know that the ability of some groups of actors to initiate research programs and guide them in particular directions can be decisive in selecting a pathway. This pathway can then become self-reinforcing on a product or a process that had no particular advantage at the start, either in terms of functional qualities or in terms of relative prices (Foray, 1989, Dockès, 2002).

That is why we have rejected, at least at this stage of our research program, the idea of working on changes in relative prices to understand the incentives to develop “green chemistry” solutions, considering that they do not clearly indicate to the agents which new processes and products are the likeliest alternatives to fossil resources. This hypothesis, supported by convergent testimony, treats DGC as an unstable universe in the sense that Godard (1993) gives the term: a universe where traditional economic calculations only partially determine the choices of the actors, in the absence of a minimum representation of their preferences and the series of processes and markets that the planned “semi-products” are likely to enter.

They therefore give special emphasis to the construction of collective representations of the future, based on which they can build partnerships and learning and “coopetition” strategies (Despeyres and Dumez (2006); the mobilization of scientists is key, because they are asked by economic actors to provide credible scenarios, intended to consolidate the change management efforts – based on *ex ante* choices made under uncertainty as to technological developments and social acceptability.

In the first section, we develop the idea that such situations lead actors to seek to achieve sectoral reorganization by forming communities to solve new coordination problems (1.1), particularly those faced by “modular innovation” strategies (1.2), to *create order* in an unstable environment by putting together objects, resources and representations of the future in terms of *community productive patrimonies (in french patrimoines productifs collectifs)*<sup>3</sup> (1.3). When significant impetus was given during the 1990s, green chemistry within the meaning of Anastas’ 12 principles was not part of such patrimonies (1.4). However, it was the agribusiness actors who organized this dynamic through a biorefinery concept that they asked the government to support (1.5).

Based on the first section, we can deduce analytically the need to describe the “ordering” of efforts to develop community productive patrimonies in both their dimension of synchronic coherence (how the actors coordinate on this effort at time *t* without standard price/market information) and in their diachronic dimension (how they project themselves *together* in the future to manage uncertainty). In the second

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<sup>2</sup> There are multiple examples of this hypercompetition. We shall see below that pyrolysis processes are almost as commonly used as enzymatic hydrolysis processes for the production of biofuels and chemicals, while some scientists are wondering whether the best path might not be to directly convert biomass into electricity. Within biofuels themselves, there is fierce competition between a variety of possible raw materials and substrates, and microalgae are seeking to make all these potential industries irrelevant. In the field of biopolymer-based plastics, similar questions abound: should the goal be recyclability or biodegradability? Which renewable polymer or intermediate chemical should technological efforts be focused on?

<sup>3</sup> Here, the term *patrimony* is used in its French meaning: *patrimoine*. It refers to both tangible and intangible assets of firms or sectors and to inherited resources that have to be preserved in the future.

section, we develop this approach to community productive patrimonies using a “narrative approach” –and in particular its methodological principle calling for establishing a clear “snapshot” of the *state of knowledge of the actors when they act* (Dumez and Jeunemaitre, 2005). First we will describe the collective initiative procedure, which is an incentive for the coordination of scientific and economic actors at a European, national and local level (2.1.). From a diachronic point of view, the effort to build community productive patrimonies that reflect these initiatives results in the exploration of technological expectations, of which we will briefly present three pathways, compiled from the literature and expert opinions (Nieddu, 2009) (2.2). The disappointments of the late 1990s led actors to take note of the inadequate integration of certain aspects of sustainable development and green chemistry (such as biodegradability), and to reorganize the rational myth of the use of agro-resources towards a biorefinery concept, proposed as a central object of the transition to renewable resources (2.3).

## 1. Community Productive Patrimonies

In this section, we base our assumptions on a particular issue addressed in the literature of innovation and production systems (Amable, Barré and Boyer, 1997; Malerba, 2002); their developments suggest both structural constraints and sources of opportunities. Their very structure plays a role in the competition that plays out over the long term and not just in the immediacy of market clashes.

The way in which technological change will be ordered can be seen in the efforts of actors *historically situated* to reorganize the knowledge bases of these systems to find new development paths consistent with their specialization. We are then interested in incentives to create long-term new “worlds of production” that involve systemic changes.

This reflects the importance of the construction of future visions to ensure convergent behaviors. These visions encourage the reorganization of knowledge bases and the organization of new communities that promote a common representation of the technological future. We will emphasize the fact that the significant failure of modular innovation attempts reinforces the actors’ conviction of the need to “create order” (see below 1.3.) in technological change. We also defend the idea that the needs of green chemistry do not play a primary role in this effort to create order, but that agribusiness actors seek to play a leading role in bringing together *communities of action* around their own projects.

### 1.1. Communities to lead the effort to reorganize skills

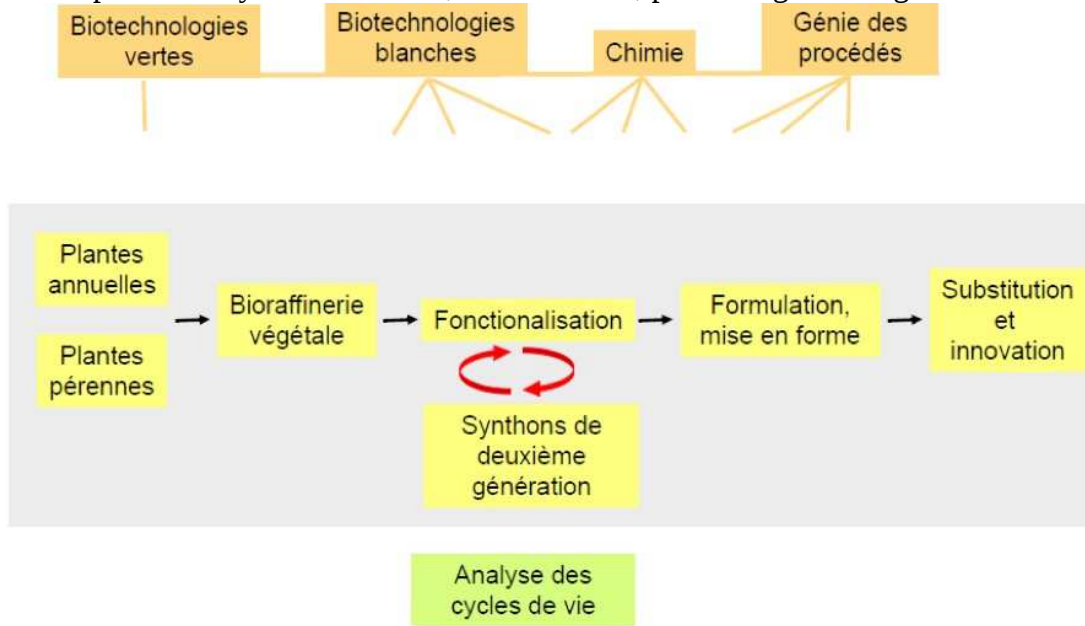
Those communities are formed around existing or developing scientific, technological, economic and social resources that are community productive patrimonies. Two dimensions are present in this notion: (1) the idea of shared resources that must be produced or identified as such and be maintained over time so that actors can coordinate, and (2) the idea of “taking power over the future” (Godard, 1990): saying that an element is *a patrimony* means that we want a future in which it is present.<sup>4</sup> If the problem is that of the emergence of a new economic

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<sup>4</sup> Where supporters of a monocausal analysis might be interested only in the commitment of monetary resources in market relations, to acquire capital and labor, or might see relations

sector, it must be considered in this long time horizon where all levels of collective action are concerned, from basic research to industrial innovation, but also the construction of business and market models. Hence the importance now given to strategic reflection, both in the U.S. and Europe, on “technology roadmaps,” which collectively set a reachable horizon and a method of coordination likely to achieve that objective.<sup>5</sup>

In forecasting studies related to the developments of the uses of biomass and agricultural resources for non-food purposes (INRA Prospective Unit, 2005; Colonna, 2006b), the actors develop an ideal representation of the changes, related to complementarity of innovations, raw materials, processing and usages.



Document 1. Colonna, 2006, CNRS Chimie pour le développement durable, 2 Oct. 2006

This approach of creating a system is the product of “technological expectations” (Hekkert et al., 2007). Advances in biotechnology during the 1980s in the field of medicine and pharmaceuticals can be transferred and linked, through the renewal of chemistry, with sectors that historically belong to different ‘worlds of production’ (agriculture and construction, plastics or automotive). The emphasis on the

constitutive of communities only in terms of strategic constraint (prisoner’s dilemma), or power and revenue (domination over a network).

<sup>5</sup> We can cite three key reference documents for DGC actors:

- The USDA DOE document (1999) “Vision” document *Plant/ Crop-Based Renewable Resources 2020: A Vision to Enhance U.S. Economic Security Through Renewable Plant/Crop-Based Resource Use*, <http://www.oit.doe.gov/agriculture/>, DOE/GO-10099-706, February 1999.
- The U.S. document identifying key priority agricultural intermediates (T Todd Werpy and Gene Petersen (ed.) (2004) *Top Value Added Chemicals from Biomass: Volume 1 - Results of Screening for Potential Candidates from Sugars and Synthesis Gas*, Report produced for the U.S. Department of Energy (DOE), by the National Renewable Energy Laboratory, a DOE national Laboratory, August 2004, 76 p.)
- The technological opportunities report developed for the European Commission by Wolf, O. et al (2005) *Techno-economic feasibility of large-scale production of bio-based polymers in Europe*, European Commission: Technical Report EUR, 22103 EN 256 pp.

importance of upstream research, whether basic or applied, aims not so much to create radically new avenues as to organize the technological trajectories that help build these inter-sectoral relationships –and therefore identify the scope of new technical-scientific and economic communities.<sup>6</sup>

## 1.2. Modular innovation vs. systemic innovation in sustainable development

From a theoretical point of view, these notions of communities and community productive patrimonies refer to the fact that in any decentralized economy, the actors must manage the division of labor and ensure consistency in the production system by organizing both synchronic and diachronic coordination mechanisms (Sapir, 1997). They are then faced with a contradiction that must be regulated. The division of labor means that production systems can be decomposed. But no actor wants to manage the entire system because it would generate overwhelming costs for him, cognitive and otherwise (Vanhée, 2008). All the actors develop strategies so they do not have to do so. One condition of the development of new technologies lies in the regulation of this contradiction.

In the field of biopolymers,<sup>7</sup> we have observed the effects of this finding in terms of strategies. The actors develop Schumpeterian breakthrough strategies that we have called modular innovation strategies (Nieddu, 2000). This involves changing the contents of a single “drawer” of the production system without incurring the cost of changing other “drawers,” either because one has created a key polymer around which other actors will be forced to gather together, or because the new “drawer” functionally replaces a less efficient element. This strategy is particularly visible in the pharmaceutical industry where a drug is assessed as being novel or more effective by institutionalized testing procedures, then replaces the older drugs (Amable, Barré and Boyer, 1997). It is less so in situations of *systemic innovation*, when the private and social returns from the innovation depend on its being adopted by the entire system (Foray, 2000).

The introduction of renewable resources or their derivatives into existing systems poses above all the problem of acceptance of processing costs (involving new technologies or skills acquisition) along a production chain, in a sectoral system of chemistry, which, according to Malerba, is strongly marked by a vertical division of labor (Malerba, 2002, 2004, 2005). But as Arkema’s Partnerships Director says, we must “change everything” without the changes necessarily implying an epistemic breakthrough: “we change the nature of the reactors, catalysts and impurities” [quoted by Latieule (2006)]. This is why we interpret the situation of biopolymers in

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<sup>6</sup> This is not a positive or negative judgment of this mechanism; these communities, because they underpin the competitiveness of the actors, both exclude and enable progress, as shown in the historical example of the communities formed by industrial agriculture around resources such as access to credit, cooperation, shared industrial tools and collaborative research. Serving a development model that has allowed rapid progress, these collective tools have also greatly contributed to the elimination of part-time farming particularly resistant to market fluctuations (Nieddu and Gaignette, 2001).

<sup>7</sup> In the late 1990s, there was semantic confusion about the term “biopolymer,” which referred to at least partly fossil-based biodegradable polymers or copolymers and polymers produced from natural substrates. Originally the term was used to describe biocompatible medical materials.

the late 1990s (Nieddu, 1999a, b, 2000) as a situation of “technological chaos,” in which the issue of allocating resources to systemic change had not been addressed, hence very few communities gathered around actors having patented what they claim are key polymers. This failure to create a community, (which we contrast in the second section with the collective strategies of building a sector), on the part of the actors of the Schumpeterian breakthrough model are perfectly summed up by Pavitt (1998): “What Adam Smith Tells Us and Joseph Schumpeter Doesn’t.”

### 1.3. Community productive patrimonies and sector in an uncertain universe

What are the knowledge bases of the formation of a community? Two sectors contribute to knowledge bases specific to DGC. The *biotechnology and pharmaceutical sector* is, according to McMillan et al. (2000) and Malerba (2002), based on a division of innovation labor between universities and private actors. This combines with the institutions regulating the ownership of the knowledge produced (patents, marketing authorizations and regulation). The knowledge of this sector was explored starting in the late 1980s in the hopes of a rapid transfer of knowledge to systems appropriable by firms in plant chemistry. Monsanto announced in the late 1990s an all “GM” solution to produce biodegradable plastics substrates directly in plants, with high yields. There was a great deal of media hype, and then the program was abandoned.

In fact, the transfers will be slower and more complex. Polylactic acid patents in the 1990s dealt with bioabsorbable wound dressings before anyone became interested in their properties as biodegradable plastics, or thought about producing them from plants. In his 2002 report, Michel Vert noted that their future depended on the development of inexpensive industrial polymerization processes, and improved thermal properties, and thus the mobilization of skills from the *chemical sector*. This is in line with characteristics described by Malerba for this sector: the importance of the vertical division of labor in R&D, the simultaneous presence of internal and external R&D (collaborative platforms or universities) to solve production problems, and the need for strong user-producer relationships in industry to successfully bring products to reality.<sup>8</sup>

The formation of community productive patrimonies corresponds to the need to recreate in a subset at least the unity and coherence of the process of developing a productive project. The corollary of the solicitation of researchers on research programs is more the attempt to form community productive patrimonies in structured economic spaces than the technological breakthrough itself. This relates to H.C. White’s economic sociology research, for whom the markets are linked to other institutional areas, and for whom “*the social and economic logic behind the existence of organizations is not derived from an imperative of rationality (bounded or not), but rather an imperative to search for stability and control in a radically uncertain environment. The strategies developed by firms mobilize different types of*

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<sup>8</sup> The sector therefore would not exist were it not for the fact that “*the increasing reliance on external links for complementary scientific and technological knowledge has led to the emergence of networks of three types: interfirms, university-industry and user-producers in specialty segments*” (Malerba, 2002:15).



*resources to achieve goals presented as desirable, and thereby generate their market identity. Organizations, through their strategies, try to create order out of the chaos that characterizes their environment.”* (White & al., 2008, p.17)

From the theoretical viewpoint, these community productive patrimonies are resources that (1) are sought for their collective value, (2) must be shared in order to exist, (3) must be considered as patrimonies to justify the effort to preserve them, in the phases of uncertainty about their ability to produce novel objects under acceptable market conditions (Nieddu, 2007). As stylized facts, the productive patrimonies are first of all intangible resources allowing for learning between users and producers (Foray, 1994), and shared cognitive tools (Zaclad, 2007), systems for recognizing and qualifying free resources, (such as scientific knowledge), and assets in their own right in the sector (Billaudot, 2004). Materially, these are “localized” systems allowing scientists and economic actors to come together around dedicated collective public and private laboratories and technology development activities (demonstrators or pre-industrial pilot plants). Then there are dedicated institutions (Barrere, 2007) and institutional community building tools that are not specific to DGC but that its actors use to a large extent, namely the technology platforms in Europe and competitive clusters in France. The institutionalization of green chemistry also provides an example of institutional resources designed to allow actors to coordinate on a common productive effort (Woodhouse and Breyman, 2005).

#### 1.4. Green chemistry and renewable resources

We said earlier that the use of agricultural resources and the notion of green chemistry did not have an automatic link. In the early 1960s, great chemists like Natta justified the “progressive” character of fossil-based chemistry by the fact that it freed up agricultural land, which could then be used to produce food. However, in the U.S. and Europe, agricultural surpluses became a structural problem in the early 1970s, while the chemical industry, based on the founding text on DDT by Rachel Carson, followed a long evolution in response to serious challenges to their professional field (Bensaude-Vincent, 2005, 2008).

In the U.S., the movement leading to the institutionalization of green chemistry was initiated for health and environmental reasons. The *Pollution Prevention Act* of 1990 and the *Environmental Protection Agency (EPA)* played a pivotal role in this area. In fact, the term *Environmental Chemistry* was used in the U.S. in the early 1980s, before the term green chemistry was coined. According to Woodhouse and Breyman (2005, op. cit., p.204) the directors of the agency considered that “*the [Pollution Prevention] Act heralded a new era in the philosophy and policy of controlling the risks of toxic chemicals... [It] served as guidance by providing a series of approaches to pollution prevention. At the top of this series is ‘source prevention.’ In other words, the ultimate approach to preventing problems with toxic chemicals is not to produce such substances in the first place.*”

The first publications in green chemistry like the 1994 symposium proceedings mention agricultural feedstocks as alternative feedstocks, but their use is conditioned by the explicit goal of reducing risk. In the introduction to these proceedings, Anastas and Williamson (1996: 6) present the logical path to improve reaction

conditions for green chemistry: “1. *Nature of the Feedstocks or Starting Materials*, 2. *Nature of the Reagents or transformations*, 3. *Nature of the reaction Conditions*, 4. *Nature of the final product or target molecule*.” Agricultural feedstocks are not mentioned, because “*in some case these four elements are closely inter-related and in some case inextricably*” (idem). The authors mentioned only the areas where it is impossible to practice green chemistry without using a plant-based substrate. Similarly, the book edited by Nelson (2004) *Agricultural Applications in Green Chemistry* refers only to environmental issues in agriculture –pesticides based on natural oils, or phytoremediation by plants that can clean up soils, for example– with the exception of one article on ethanol extraction by fermentation.

Initially, activities based on agricultural resources emerged in response to agricultural surpluses, which became widespread in the 1970s, and the need for new sources of activities ensuring the presence of industries in rural areas. It was primarily an issue of production overcapacity. Community productive patrimonies in DGC were thus formed by groups of growers and agro-industrial firms, in a context of agricultural policy reform, before chemical corporations became involved.

### 1.5. The “comeback” of agriculture in chemistry

The central role of agribusiness stems from two factors that explain the early projects of agro-industrial actors: First, they remembered the non-food industrial uses of agricultural products (including the transformation of surpluses into alcohol and attempts to provide alternatives to certain raw materials before and during World War II).<sup>9</sup> Second, because of their organization in agro-industrial producing areas, they were accustomed to building economic circuits of first-stage processing and shipping of intermediate agro-industrial products (for example starch used in the food industry or paper) (Nieddu and Gaignette, 2001, op. cit.). This continuity of food and non-food was all the stronger when DGC technologies were in line with those of food engineering.

Moreover, the alternatives sought by these actors did not target just oil. Chemical alternatives to competing *intermediate food products* were also sought, in the field of food additives, for example. European directives facilitated this competition, considering that in 1988 flavorings produced through biotechnology were considered natural (and more recently that they are not included in the scope of the REACH directive).<sup>10</sup> In this 2006 reference book there was a chapter devoted to the

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<sup>9</sup> A. L. Young, (2003, p.273) states that “... all Ford cars were finished in an enamel in which soybean oil was used extensively (it was estimated that about a half-bushel of soybeans were used in the manufacture of every Ford car). By 1941, Henry Ford had produced his first automobile with an ‘all plastic’ body. The car climaxed a dozen years of research based on Ford’s long-standing belief that someday he would ‘grow automobiles from the soil’ [2]. The car made its appearance when a steel shortage threatened to cripple the automobile industry’s non-defense production. Unfortunately, World War II forced industries to focus on meeting the needs of the Defense Department and plastic vehicle bodies had no place in the war effort. This story of Henry Ford and plastic from soybeans is a lesson on how difficult it is to promote and sustain innovation. Almost 50 years would pass before both the industry and the public would again embrace bio-based products.”

<sup>10</sup> See [http://www.dgccrf.bercy.gouv.fr/manifestations/colloques/aromes\\_alimentaires/08\\_guerere.pdf](http://www.dgccrf.bercy.gouv.fr/manifestations/colloques/aromes_alimentaires/08_guerere.pdf), for a debate on flavorings, dated 12 avril 2009.

substitution of vanillin by extraction of ferulic acid from industrial by-products of beet or residues of starch manufacture (Lesage-Meessen et al., 2006).

## The substitution strategy, towards a biorefinery model?

Traditionally non-food crops, such as hemp and flax, are being revisited for their specific properties (Garnier et al., 2007). Agricultural actors, major grain companies such as Cargill, and starch manufacturers such as National Starch, Roquette and Novamont are seeking to expand the uses of intermediate agro-industrial food products to chemical intermediates used in plastics processing: starch, key product of the research of the 1990s (Bastioli, 2001). Others are working on the potential of plant protein or milk powder, an inexpensive substrate due to surpluses, whose use is as common as starch in industrial food engineering (Prochazka & Assezat, 2008).

But the search for non-food uses of agricultural products was, after the first oil crisis, dominated by the figure of the “biorefinery,” related to the energy paradigm.<sup>11</sup> Forming networks collecting agricultural raw materials around a refinery and local savings or national aid to rural areas is only a reproduction of the methods for creating collective agro-industrial systems through agricultural cooperatives, which had been instrumental in the success of the “thirty glorious years” in France (Nieddu & Gaignette, 2001, op. cit.). We find this mobilization of rural communities around the first ethanol production plants in the United States.

According to the literature, and interviews with local actors of the first developments of the 1980s, the biorefinery processes explored used the petrochemical process of steam cracking. After grinding, the raw material was pre-processed (equivalent of distillation and petrochemical steam cracking), by physicochemical processes under pressure either by thermal hydrolysis, or by steam explosion of the cellulosic biomass, under acidic conditions, leading to the use of sulfuric acid as in the AFEX process considered to be well suited for herbaceous plants selected for experimentation in some French regions, while forested countries like Canada and Finland explored other avenues (Ballerini, 2006). The U.S. National Renewable Energy Laboratory researched two types of platforms: the first, called the “sugar platform” is based on the fermentation of sugars extracted from biomass feedstocks to form biofuels, the second, called the “syngas platform” is based on gasification of biomass feedstocks and by-products from conversion processes.<sup>12</sup>

In the following sections, we will look closely at the dynamics that are rooted in the needs of agriculture and agribusiness, and which predominantly seek to reorganize a sector on the basis of biotechnology knowledge. Quite logically, other actors may be developing other concepts of productive patrimonies and exploring

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<sup>11</sup> For example, the French Carburol program of 1979. It developed especially in the U.S. and Europe during the 1980s when set-aside measures were considered an inevitable turning point. Energy uses were the main focus of the first European FPRDT in 1984. Uses other than energy appeared in the “First multi-annual programme for bio-technology-based agro-industrial research and technological development (ECLAIR), 1988-1993” of the second FPRDT.

<sup>12</sup> See <http://www.nrel.gov/>. The second platform seemed to us less strongly linked to DGC than to energy, in the 1990s. The attempts to produce energy by gasification in the 1990s were deemed a failure in a study of the Dutch industry (Negro et al., 2008). Nevertheless it should be noted that these authors and others believe that depending on products targeted, the gasification industry remains relevant.

other avenues, based on their own resources that they are seeking to promote. For example, in France, the CEA is exploring a thermochemical gasification of “lignocellulosics” (wood/straw, or specific crop), in a program on 2<sup>nd</sup> generation biofuels, in coordination with the French Petroleum Institute (IFP). It is understandable, due to its position in energy production, that the CEA is studying the use of outside energy in the processes, which corresponds to the research it is conducting in parallel on hydrogen and electricity.

## 2. Towards DGC? The mutations of a rational myth

In the first section we suggested an analytical framework in which assembling collective resources was a central component of the actors’ strategies. The “ordering” of a new economic model raises a number of challenges and difficulties for the agro-industries. This “ordering,” which is the assembly of resources to be included in the community productive patrimonies of the sector being developed, is done based on a certain representation of the future, which must be analyzed in light of the issue before us: the sustainability of the effort of technological change management in a context of doubly green chemistry.

It is therefore necessary to *substantively* describe community productive patrimonies, which cannot be reduced to a monetary value, but will be both tangible and intangible assets (the representations of the future should be considered as having assets with economic value, even if it is not calculable unless an ad hoc agreement is reached). This is why we have documented the various avenues explored. Biorefining thus appears to be a direct expression of what can be called, drawing from Hatchuel (1997), a rational myth, namely a path of engagement, on a path of exploration of technological expectations, coupled with the idea that the “long-term vision” must prevail over the current difficulties, and expectations of development must prevail over information provided by economic calculation.

The documentation of the formation of community collective patrimonies as we have described them in the first section (problem of mobilization of knowledge, systemic reorganization rather than modular innovation and integration of the principles of green chemistry by central actors in the dynamics of formation) leads us to observe technological change in specific dimensions (Nieddu & Garnier, 2008). We are particularly interested in variables related to the internal logic of the technological system, independent of and often prior to pricing issues, because the viability of technical objects stems primarily from their ability to enter technologically efficient combinations (Gonod, 1991). We will of course observe how variables related to the social acceptability of the technologies are involved in the matter at hand. Finally, we have seen that we must pay attention to how actors try to define their concept of division of labor, alliances and division of the productive system into “sets” they see as coherent.

We will look primarily at the example of France to describe the mobilization of institutional resources, at the European level (or even transatlantic collaborations as in the case of biorefining) down to the local level (2.1.). Then we define the three types of technological expectations around which these communities choose to gather private and corporate resources (2.2.). We will conclude with the mutations that reality imposes on the scope of these communities (2.3.). We believe that there

are two such mutations. First, in the 1990s the solutions promised by large polymers (the “all starch” or “all PLA”), were overestimated and the technological complementarities necessary for the existence of new products were underestimated. This led in the late 1990s to seek development shortcuts through renewable polymer composites - polymers derived from petroleum chemistry, but their “sustainable development” identity was fiercely debated, which led to the search for other technological complementarities (2.3.1). Second, the term plant refinery was replaced by biorefinery, both to gain societal legitimacy and to formalize new inter-industry relations to achieve a new decomposition of the production system around intermediate products from renewables using biotechnological processes (2.3.2.). But those who want to produce these intermediates are still looking for suitable collaborations.

## 2.1. Mobilization of institutional resources

The institutional systems described here all largely rely on the scientific research incentive procedure via *research project initiatives*, under the condition of ties to business. These systems combine local sectoral organization initiatives and national and European institutional action. To be sure, these are public action procedures that are today generic; nevertheless, they play a special role in our case. Indeed, agriculture and agro-industries follow learning dynamics based on technological knowledge that is largely external: the firms involved (see below 2.3.2 c) therefore adopt the path explored by industry rather than an individual path, following a behavior modeled by Llerena and Oltra (2002).

European mobilization was achieved by ramping up the theme in the framework programs. Originally turned to energy, the framework programs bring together the knowledge bases from projects on non-food crops, energy, materials and biotechnology. Because these four fields contain resources useful to others, policy-makers sought to unify these knowledge bases to drive the sectoral reorganization. In particular, the strategy of the SusChem technology platform is to organize cooperation between so-called white biotechnologies, materials technology and reaction and process design.

### Doc2. History of the framework programs for research and technological development related to non-food

Non-food	Biomass Energy	Materials	Biotechnology
<b>First Framework Programme (FP1) - 1984–87</b>			
	Energy from Biomass		Biotechnology Action Programme
<i>Single European Act – science becomes a Community responsibility</i>			
<b>Second Framework Programme (FP2) - 1987–91</b>			
ECLAIR	Energy from biomass within Non-Nuclear Energy JOULE		BRIDGE
<b>Third Framework Programme (FP3) - 1990–94</b>			
AIR – Non-Food J	JOULE II - THERMIE	AIR – Non-Food	Biotechnology (I)
<b>Fourth Framework Programme (FP4) - 1994–98</b>			

FAIR – Green Chemicals	JOULE III - THERMIE	Forest/Wood	Biotechnology (II)
<b>Fifth Framework Programme (FP5) - 1998–02</b>			
QoL KA 5	ESSD	GROWTH –	QoL KA3 QoL KA3 – Cell Factory
<b>Sixth Framework Programme (FP6) - 2002–06</b>			
	ESSD	GROWTH	Life sciences, genomics and health
<b>Seventh Framework Programme (FP7) - 2007–13</b>			
<b>Food, Agriculture and Fisheries, and Biotechnology (KBBE)</b>	Energy	Nanosciences, Nanotechnologies, Materials and New Production Technologies	Within KBBE (Knowledge-based bio- economy)

Source: Combs, 2007

In France, the mobilization of actors in the 1980s led in 1994 to the creation of Agrice, a scientific interest group supported by the government, ADEME, agricultural organizations and industry partners.<sup>13</sup>

The mobilization at the local level of agro-industrial production areas, to promote agro-industrial competitiveness, is the third feature of this projects method. As forums for sharing between government and private actors, the organizations created in the early 1990s, such Europol'Agro in Champagne-Ardenne, the Centre de Valorisation des Glucides en Picardie in Picardy and the Plateforme régionale Agro-Bio-Industrielle de Lorraine (PRABIL) expanded the call for projects method, both to guide research units to the area and encourage them to provide “state of the art” knowledge to establish a regional strategic thinking and plan the efforts of these units over time. This regional mobilization approach was integrated in 2004 in the new industrial policy of competitive clusters. This led to the following configuration: Plant-based agriculture was organized into Industries and Agro Resources (IAR), a “*cluster with a worldwide vocation*” promoted by the Champagne-Ardenne and Picardy regions. Meanwhile, a major agribusiness, starch manufacturer Roquette, created *Biohub*, another community of actors that also received support from the government, approved in December 2006 by the European Commission.

Thus the organized actions involved in DGC in France are fragmented among different communities. The Axelera cluster, organized around leaders of chemistry in Rhone-Alpes, works on renewable resources through the recommendations of green chemistry. The IAR cluster coexists with the Biohub network. These two communities began to converge in the “*plant chemistry*,” association originally initiated by Roquette, which “*aims to bring together the major economic actors in agribusiness, chemistry and their downstream industrial customers, who engage in*

<sup>13</sup> AGRICE promoted non-food agricultural crops, bringing together professional organizations involved in oilseeds (ONIDOL), cereals (AGPB) and beets (CGB) and public research organizations (the French Institute of Petroleum, INRA, CNRS and ADEME) under the aegis of the ministries of agriculture, industry, research and the environment. The companies, Totalfina, Elf, Limagrain and Edf joined the organization, which was renewed in 2001 for a period of 6 years and expanded to include the following stakeholders: research organizations of the Commissariat à l’Energie Atomique (CEA), the companies Arkema, Bayer CropScience, Cerestar France, Eiffage Public Works, L’Oreal, Rhodia, the funding organization Oseo. Agrice was dissolved and replaced by a Biopolymer program in 2008.

*the industrial development of plant chemistry in France and Europe.*” The ties between IAR and Axelera illustrate the effort to create community productive patrimonies in light of the “*need to create an industry ‘driver’ that would bring together all upstream and downstream actors in the bio-resources sector.*” (Axelera Newsletter, No. 7, 2007, p. 2).

## 2.2. Three avenues of mobilization on technological expectations

The notion of technological expectations (Brown et al., 2003) aims to describe the fact that the actors make use of scientific advances to explore the development cycles of specific technological opportunities, and test scenarios for matching specific supply and demand. Despite overly optimistic “initial technological promises,” which were common in the case of agricultural resources as evidenced by the announcements of the construction of production capacities throughout the 1990s, these initial representations do nonetheless have value.

Mere mention of these promises has real economic effects. It attracts the attention of funders and stimulates the development of technical and political agendas that can constitute “protected areas” on development niches that are treated as ‘patrimony’, i.e. preserved from profitability calculations until they have reached maturity.

### **An example of the rational myth and technological expectations related to doubly green chemistry in a scientific journal**

“Green materials are the wave of the future. There is immense opportunity in developing new bio-based products. New environmental regulations and societal concern have triggered the search for new products and processes that are compatible with the environment. The incorporation of bio-resources in composite materials can reduce further dependency on petroleum reserves. The major limitations of present biodegradable polymers are their high cost. Renewable resource-based bioplastics are currently being developed, further research should overcome the performance limitations.” (...) “Eco-friendly bio-composites from plant-derived fiber (natural/biofiber) and crop-derived plastics (bio-plastic) **are novel materials of the twenty-first century** and would be of great importance to the materials world, not only as **a solution to growing environmental threat** but also as **a solution** to the uncertainty of petroleum” (Mohanty et al., 2002, p.20)

By interviewing a number of experts, we identified in the early 2000s three avenues of mobilization on technological expectation cycles that organize strategies for alternatives to fossil-based products.

The first consists of trying to take advantage of the qualities of the various components of the plant, and the complexity of living organisms. Hemp concrete and composites containing flax fibers (to reduce the use of fiberglass as a matrix for resins in boats and cars) are good illustrations (Garnier et al., 2007, op. cit.). This strategy is particularly clear in the marketing discourse of Vegeplast, which produces an alternative to *single-use plastic parts*, with VEGEMAT®, a composite described as deriving its properties from the simultaneous presence of fibers (as reinforcement that improves the mechanical properties), starch (thermoplastic properties), proteins (thermoplastic properties), lipids (lubricating action useful in the process) and additives (natural, of course). This avenue is not for small businesses only: for example, in 2008 Dupont introduced a similar product, “Biomax® TPS Renewably Sourced™” licensed from the Australian company Plantic.

The breakdown of plant material led to another strategy consisting of isolating a natural polymer (e.g. starch) and “functionalizing” it, endowing it with specific functions that serve a market. The treatment may be chemical (addition of a

reagent), or photochemical (grafting of organic additives on starch by radiation therapy), thermal or mechanical, to provide the desired functional qualities. Functionalized polymers can also be used in composites. Part of the Amival regional program in Champagne-Ardenne headed by C. Bliard focused on this type of process; and the Lignostarch program mixed two natural polymers, starch and lignin, lignin being a hydrophobizing agent of starch. In early 2009, Roquette announced it was working on functionalized polymers (GaiaHub).

The third avenue is “biorefinery” which breaks down the starch, cellulose and hemicellulose of the plant to obtain the building blocks<sup>14</sup> of the chemical industry. The structure of the chemical industry is particularly important here. Its vertical division of labor has as its starting point the “key intermediates” (Buffenoir, 2007). It is for these key intermediates that alternatives are sought. The case of polylactic acid (PLA), is instructive from this point of view: in a 1998 survey, Cargill researcher J. Lunt presents two other avenues, the original petrochemical avenue, which allowed the development of PLA, and the microbial fermentation avenue of producing lactic acid from renewable material (Lunt, 1998). This was a “one to one” substitution strategy. Similarly, recent programs aim to optimize a production process of ethylene, a traditional petrochemical intermediate, from bio-based chemistry (ethanol) and an enzymatic process.

Based on what has been stated above, there are clearly a variety of technological avenues. This reflects the fundamental uncertainty perceived by firms as to the future of the competition between the different technological sectors possible. In other words, the “extensive” learning processes (or learning from diversity, see Foray, 1994; Larrue, 2004) are far from over. These processes are particularly

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<sup>14</sup> Building blocks can be defined as small molecular weight molecules (MW <250-300) with at least one functional group allowing for reactivity. They can be used for building molecular assemblies using combinatorial techniques. Chemists call these “molecular building blocks.” The starch, glucose, fructose, etc. or bio-based synthetic gasses extracted from plants are considered intermediate platforms of production of these monomer building blocks used in chemistry.



important in the present case in that ago-industry seeks to valorize the entire plant. The question is whether to find a methodology that transforms all the plant co-products in the same way, such as transforming all the plant parts into synthetic gas, or whether to explore (at potential high cost) different technological solutions for each co-product.

The actors also seek to define strategic fields where relational, material and research resources will be focused<sup>15</sup> and attract other actors who are also competitors; these fields where the socio-technical and scientific networks are mobilized can be that of a raw material (hemp, miscanthus, starch, etc.) or a key intermediate that should be explored (glycerol, succinic acid, furfural, etc.) or a key process around which usage communities must be stabilized (biorefinery).

Each time, these actors claim to have an ideal development plan for a sustainable development solution both in terms of CO<sup>2</sup> emissions and in terms of the market. How does this ideal, a direct expression of a rational myth, evolve when a *disappointment* (Brown, 2003, Ruef & Markard, 2006) occurs? Especially when the results of exploratory work show that the substitution will be more complex and longer than originally planned? To be sustainable, the effort to transform the production system requires justification, in the absence of tangible results, to get the research actors (firms, public or private laboratories) to persevere in the indicated direction, meaning that the expectations are stronger than the technological setbacks. These evolutions of the rational myth are seen in the adaptive strategies on biopolymers on the one hand, and the biorefinery concept on the other.

### 2.3. The redeployments of the rational myth

Two major turning points occurred in these fields. The first, which dates back to the early 2000s based on the literature, is the calling into question of the strategic field of starch and PLA, products once seen as hugely promising, especially in plastics. These products do not appear to have the desired functionalities, unless

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<sup>15</sup> The theory of these fields is based on Bourdieu's field theory, because it contains all of the components, including *habitus* regulating the strategic behavior, a logic of *position* inside the field and *illusio* leading an actor to think that this field is the relevant location to conduct its activities. As a social universe, the Bourdieu field is where agents who occupy a position in the field are both enacted by their habitus and acting, participating in the ongoing rebalancing of the field and the constant redefinition of its issues (Lahire, 1999). It contains a **principle of inclusion** in the sense that it is a microcosm, which if it is included in the global social space, is defined with respect to this space because of its (always relative) autonomy. It is historically constituted around a law that is specific to it and makes it relatively independent of external economic logic (innovation within it is inappreciable according to these external criteria). The autonomy of the field is measured by its "**refraction**" ability of external determinants; it is never completely a "reflection" of the socio-economic power relationships outside the field, but is a "specific mediation" between the external and internal logic. The field is therefore a structured space of positions, a network of objective relations between agents who define each other by a common set of skills. In the specific case of agricultural materials, it is the epistemic community of members of the field that accumulates this specific skill set. The struggles are intended to appropriate this set of skills but may also seek to redefine it, in which case, they can profoundly alter the configuration of the field by radically redistributing the capital according to the new standards imposed. What Bourdieu calls specific capital is what we call community patrimony. This is because the actors can be both competitors on one aspect of the collective action and members of non-competing groups within the meaning of Cairnes (Dimou, 2006) on another aspect.

enriched with combinations and complementarities that were not originally planned (2.3.1). The second, which dates back to 2004-2005 (Wolf et al., 2005) according to official U.S. and European reports, is the formalization of the strategic approach of turning green refinery into “biorefinery” to produce key chemical intermediates (2.3.2).

### 2.3.1. Modified starches and “all-purpose polymers”: towards a specialization?

In the 1990s, broad claims were made about TPS (thermoplastic starches), PLA obtained by fermentation of sugars or microbial polymers. This tendency to claim that TPS *alone* had a very broad range of features is counter-intuitive based on what we know about technological objects: very few are the product of unitary technologies.

Ubiquity of PLA: technological expectations around a key polymer that do not specify what technological combinations the polymer must be included in to be functional (Schwark F. 2009, p. 648)	
Main application areas Examples Industrial applications	Agriculture, forestry, Fisheries, Civil engineering and construction industry
Medical applications	Bonding, Closure, Separation, Scaffold, Capsulation
Packaging and daily use applications	Bags, Food packaging, Packaging of consumer goods, Food tableware Bottles, Containers, Decorative parts, Films, Kitchenware, Labels, Laminates Non-wovens, Toiletries, Carpe,

The situation with PLA also occurred with TPS, which had raised great hopes in the early 1990s. In the following years, however, it became clear that not enough was known about their basic structure to achieve the desired functionalities<sup>16</sup>. Bastioli, (2001: 355) found after 10 years of investment in the field that: “*In the sector of food packaging biobased materials are not used extensively because of the high price, the non ideal water barrier properties and the limited research efforts on the interaction between the packaging material and food products (...)*.” By following the evolution of certain researchers on the basis of monographs, we found that the research strategy of modifying native starches transformed in two stages, when it appeared that the research programs were not achieving the functionalities sought.

Due to the first disappointments, starch came to be considered a simple filler material during the years 1995-2000. It was mixed with petroleum-based synthetic polymers, such as polycaprolactone, introduced to achieve the desired functionalities, including, paradoxically, biodegradability. This strategy led to copolymers that were fragmentable rather than actually biodegradable. Because of the controversy surrounding the biodegradability of these products (Jianmin Fang & Fowler, 2003:83<sup>17</sup>, Ren, 2003), this avenue was closed, and research was focused on

<sup>16</sup> The chemists interviewed describe petrochemical-based products as “statistical,” “amorphous” and “linear” while starches are difficult materials because they are “extremely well-structured,” “hyperbranched,” and “capable of autostructuration.”

<sup>17</sup> “*In order to overcome the inherent hydrophilicity of starch, blends with conventional hydrophobic synthetic polymers (e.g. polyethylene or polypropylene) have been considered for the*

copolymers made entirely from renewable resources (Bewa, 2006) at the cost of a reorganization of the communities and knowledge bases mobilized.

A strategy of systematic exploration of all possible blends of renewable polymers was undertaken to obtain the functional qualities expected.<sup>18</sup> Research then turned to other complementarity approaches by exploring other technological expectation cycles. In keeping with the scientific trends of the time, the investigations focused in particular on the potential of nanoscience. For example, nanoclays developed at the frontier of inorganic and organic chemistry (organically modified clays) were mobilized to provide the functional properties that were difficult to achieve with natural renewable polymers. Increased focus in the literature shows that nanocomposites, because of their ubiquity, played the same role as TPS or PLA in the 1990s in terms of coordinating the rational myth [see Hasmutkh et al., 2006, Chivrac et al., (2006, 2007, 2008), Bordet et al., (2008) and Joshi, Satish V. (2008) and the Bibliography of carbohydrate polymers / Carbohydrate Polymers 2006 to 2009].

<b>Polymers, between broad claims of substitution and early specialization on specific functional qualities</b>			
Table developed based on Bewa (2006), Joshi, Satish (2008), complemented by our internet watch (Nieddu 2009)			
Polymer targeted for replacement	"Natural" polymer	Manufacturers	Applications
Polystyrene	Thermoplastic starch (=TPS)	National Starch and Chem. (U.S.):Eco-foam; Novamont, Italy: Mater-Bi®; Rodenburg, Netherlands: Solanyl ®) BIOP, Germany: BIO-Par®)	Packaging, foam, loose packing, molded parts
LDPE (low density polyethylene) and HDPE (high density)	PLA (fermentation)	Copolymers of Natureworks PLA, (joint venture between Cargill and Teijin Ltd Japan Hyacil, in the Netherlands, and Toyota's Ecoplastics division are planning commercial production	Food Packaging (transparency, good mechanical properties and adequate moisture permeability but not above 60° C). Blends of fibers in automotive interiors, upholstery and trim
Polypropylene PP LDPE HDPE	Microbial polysaccharides (PHA PHB) polyhydroxy polyesters	Proctor and Gamble (Nodax®) Metabolic (Biopol®) USA, Biomer®, Germany	PHB: melting point, crystallinity and glass transition temperature similar to those of polypropylene (PP), better resistance to solvents and ultraviolet light
Polyesters	Microbial biopolymers (Polyesters composed of two different monomers (succinic acid + dialcohol like 1,3-propanediol)	Metabolic Explorer (Fr.) Sorona®: petroleum-based thermoplastic polymer resin and Bio-PDO	High performance polyester textiles, cosmetics and body care and glycol industrial applications. In formulation in a variety of products including composites, laminates, wovens, aliphatic polyesters, antifreeze
Multifunctional additive	Nanoclays	Southern Clay Products, Inc. (A subsidiary of Rockwood Sp, December 2005 acquisition of developer Süd-Chemie) Cloisite® and Nanofil®: additives (organically modified on	The "Melt intercalation" method is considered compatible with the usual industrial processes (extrusion and injection molding) and does not require solvents. These improvements include higher

*production of plastic bag and commodity products. However, the physical mixing of non-biodegradable polymers with 6-20% of starch affords materials in which only the starch portion is biodegradable, leaving the porous and hardly biodegradable synthetic polymer behind. This approach, therefore, cannot be recommended" (Jianmin Fang & Fowler, 2003 p.83).*

<sup>18</sup> See the evolution of the research of L. Averous (<http://averousl.free.fr/Publication.html>).

nanoscale). Claimed to improve the strength, increased storage modules, properties of injection molded parts less heat distortion, lower gas for the automotive industry, flexible permeability and flammability, and and rigid packaging (films, bottles, better biodegradability trays), in electronics and wire and cable coatings

In this search for complementarities, emphasis was placed on a combination of recyclability / compostability of materials from DGC rather than just biodegradability. The actors asked experts to help position the natural polymers according to their respective capacities as alternative to fossil-based polymers, rather than to continue to make overly-general claims about their potential: it is here that they seek to forge collaborations for learning about the uses, and where we see the logic of community patrimonies.<sup>19</sup>

An example of the requalification of the potential for substitution by PLA (Kosior et al., 2006)							
	LDPE	PP	HDPE	PS	HI-PS	PVC	PET PA
Potential	+	+	+	+/-	+/-	-	++ +/-
(substitution : ++; Probable: +; Possible: + / -; Doubtful, -)							

### 2.3.2. Anchoring the concept of biorefinery in the economic landscape

The concept of plant refinery was originally considered mainly as a source of biofuel production. Biofuels had the double disadvantage of being difficult to balance economically and producing by-products that were if not undesirable, at least difficult to abandon in landfills, from a green chemistry standpoint. In the early 2000s, the concept appeared fragile, both in terms of social acceptability and for technical reasons, masked for a time by the hopes generated by rising oil prices, but exacerbated by tensions that these expectations generated on the food commodity markets.

#### a. Global requalification of the coherence of the plant refinery project

Hence a strategy to collectively strengthen the project by requalifying it: the concept of “biorefinery” was specifically intended to codify a general philosophy of use in the chemical industry of agricultural feedstocks (technical perspective) and its coherence in terms of sustainable development (societal perspective). Various operations were conducted by U.S. and European actors including a joint Europe-United States working group beginning in 2004, and European projects funded to explore the social acceptability of the concept (Biorefinery Euroview and Biopol). These projects, supported by the 6th FP were explicitly dedicated to construction of the long-term “vision” of development of biorefining (Christian et al., 2007). Simultaneously a study of the reactions and social acceptability of the concept was commissioned (Peck et al., 2009).<sup>20</sup>

<sup>19</sup> For example, in plastics, determining the right machine settings is always difficult, hence the idea of cooperation and sharing of information to identify the real, not theoretical, potential.

<sup>20</sup> Similarly, biorefining actors sought to distance themselves from the recent craze for biofuels. The recent discourse emphasized the refining of non-food plant parts and the use of new resources (municipal waste and ligno-cellulose). The conference in December 2008, “*Biopolymers, Biomaterials, Green Chemistry*”, was part of the program “Chemistry for Sustainable Development”,

The research produced within the framework of the European projects *Biorefinery Euroview* and *Biopol* demonstrated the coherence of the concept in terms of sustainable development. Biorefineries were no longer presented as independent production plants, but as a local group of companies using each other's co-products. These industrial complexes therefore organized savings of flows and materials in line with the principles of industrial ecology, as illustrated by the success of the complex in Kalundborg.

## b. Biorefining refocused on a limited number of key intermediates

The *Biorefinery Euroview* project identifies four types of biorefineries based on raw materials: cereals, forest-based and lignocellulosics, oilseeds, and finally "green," meaning waste. This diversity makes the "biorefinery project" robust: development does not depend on a single resource, and the concept can accommodate various types of land, thereby expanding the coalitions of actors around a model.

Documents on biorefining often provide a wide variety of theoretically possible options: for example, cereal-based biorefinery describes the extraction of starches (chemically converted into TPS or hydrolysates to produce ethanol and other precursors), proteins and oils (leading to hydrolysates); and lignocellulosic materials from straw undergo cracking which leads to carbon chains (pentose or hexose sugars, known as C5 and C6 in chemistry) and residual lignin that can be gasified and then converted by the Fischer-Tropsch process into fuels or chemical precursors.

But how to create order out of the almost infinite opportunities for transformation, when there is so much flexibility that we imagine we can produce any key intermediate "equivalent" to a petroleum-based intermediate from agricultural substrates, or even produce the petroleum-based intermediates themselves (ethylene or butadiene, for example)? How to reduce the variety and focus on real markets? One can notice here a deepening of the logic of community productive patrimonies: Based on forecasting studies, the public and private actors were encouraged to focus their efforts on just a few key intermediates. The 2004 U.S. Department of Energy report identified 12 "key intermediates" as promising according to experts. The industrial focus then shifted to this list of precursors and their uses (Werpy & Petersen ed., 2004; McKinlay et al., 2007), in particular glycerol, succinic acid, and isosorbides.

## c. Businesses between appropriation and collaboration

The technological "roadmaps" on key intermediates are expected to lead private firms to appropriate the production processes. This movement of economic

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and was introduced by the following considerations: "*Energy needs alone represent about 90% of oil consumption, and can only partially be met by the production of plant biomass, with the risk of inducing adverse effects on the equilibrium of agricultural commodity markets and the availability of food resources. However, valorization in chemistry and materials appears to be compatible with the more limited size of these markets (about 5% of fossil carbon) and with the higher added value of petrochemical products compared to that of energy.*"

appropriation does occur, but based on our communication watch, these firms still cannot avoid pooling the knowledge bases from biotechnologies. On the one hand, the strategy of producing intermediates allows a decomposition of the production system.

This is probably based on the idea that the replacement of petroleum intermediates makes it possible to integrate chemistry without causing major changes in the economic cycles and positions of the actors. On the other hand, as in the case of plastics made from starch or PLA, the complementarities between technologies have not been fully explored, both in the agro-industrial intermediates segment and in the learning that this segment must acquire with its downstream users, the novelty probably being that this learning is now being included in some programs (Garnier et al., 2008).<sup>21</sup>

**A “textbook case”: isosorbide**

“... One product in particular stands out among the candidates (biosolvents, biolubricants) that the white biotechnology industry and the BioHub program are actively developing: isosorbide. As a synthetic intermediate or comonomer made from cereal starch, isosorbide can be used in the production of various plastics such as PET (polyethylene terephthalate). Note however that only the first step, the conversion of glucose, uses enzymatic degradation processes. The two subsequent steps, hydrogenation and dehydration, are fully chemical. This illustrates that in most cases, white biotechnology still needs to use traditional synthetic chemistry processes. Technologically, the use of isosorbide is of particular interest for the plastics industry, because it makes polymers and PET much more heat resistant, making it possible to use PET for hot-fill containers.”<sup>22</sup>

Excerpt from **Arnaud Queyrel (2007)** *Chimie verte, Une solution à (bien) évaluer*, [http://www.bulletins-electroniques.com/ti/139\\_06.htm](http://www.bulletins-electroniques.com/ti/139_06.htm)

In addition, while seeking to appropriate the production of key intermediates, leading firms in the sector were all trying to forge collaborations. (1) Thus, apart from isosorbide, Roquette claimed the exploration of both succinic acid and glycerol, but to do so, forged collaborations with other companies that could bring them a portfolio of technologies, and with universities holding the patents on the catalytic enzymes, (Rice University for succinic acid). (2) On the same key intermediates, ARD, the research and development firm supported by the Champagne-Ardennes consortium of grain and sugar cooperatives, proposed a number of valorization projects, creating a subsidiary for each product. For succinic acid, it created Bioamber, a joint venture with DNP Green Technology, which held licenses to fermentation enzyme patents of the U.S. Department of Energy (Erbert, 2007). (3) The start-up Metabolic Explorer presents on its site an economic model in which it negotiates exclusive production licenses by region or application.

Thus, though each of these actors possesses the know-how in its own field, there are serious questions as to the ability to produce the complete processes through to the final objects. Arkema, no lightweight in the chemical industry, had to develop a partnership with a German laboratory to evaluate the performance of new catalysts to convert glycerol to acrolein and acrylic acid. This shows that the processes are far from being optimized.<sup>23</sup>

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<sup>21</sup> The Matoren project in the Champagne-Ardennes region calls for exploring potential solutions in cooperation with plastics cluster Oyonnax, whereas previous programs provided only for the individual commitment of firms seeking to appropriate new technologies.

<sup>22</sup> Since then isosorbide use has diversified: in 2009, Roquette announced an isosorbide diester, Polysorb ID, as an alternative to the phthalate plasticizers targeted in the REACH directive.

<sup>23</sup> Arkema, a major player in acrylics chemistry, turned to HTE because this company specializes in intensive experimentation with catalysts. The project consisted of providing performance screening

The fact that companies cannot avoid building community patrimonies is also demonstrated in what they claim in terms of production capacity. For example, ARD claimed the installation of a 2000 t unit, announced in December 2008 for September 2009, and Metabolic Explorer claimed the construction of pre-industrial pilot plants. DSM and Roquette announced a pilot project of “several hundred tons in Lestrem” without specifying a production capacity, by late 2009.<sup>24</sup>

The information available seems to indicate that when plant chemistry companies claim production plants, it is also a way to advertise themselves as serious partners, and maintain the credibility of the rational myth around which they seek to promote the partnerships they need, not only to create novel intermediates, but also to finalize these semi-products.

## Conclusion

In this account of sectoral reorganizations performed by the agro-industrial actors, we sought to trace the modalities of mobilization in the scientific world, to form the basis of what is potentially a new sector. It seems to us that detailed descriptions of the origins of the actors, the avenues they have decided to explore, the institutional resources mobilized and the scientific and technological barriers they have encountered have an explanatory scope that an analysis in terms of price and production costs cannot have (except when they can be estimated in a complete and plausible way by the actors). This could also lead to a discussion of processes of elimination or selection of the avenues we have mentioned, a discussion which we realize is important, but that is not the subject of this article.

The notion of community productive patrimonies has been used dynamically since they are structured around rational myths. The point is to report on a situation and a period of focusing actors around technological avenues, which they also build with a view to organizing the field on which they will compete. In our opinion, this perspective makes it possible to renew the study of how the world of science is solicited, and interpret the signals sent by the actors on competing avenues. If “whole plant” biorefining is confronted and challenged by other technological avenues, the same yardstick must be used to measure their pretension to be producers of major synthetic intermediates, to look beyond the media hype that any actor tries to produce periodically. Thus, the announcement by Total in March 2008 of a pre-industrial pilot plant and U.S. announcements confirm that the avenue of

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for new catalysts to convert glycerol, a co-product of biodiesel, into acrolein and acrylic acid. Despite holding patents in this field, Arkema chose HTE in Heidelberg because they use a proprietary parallel testing technology that speeds up the testing of catalysts. This high throughput testing approach shows the growing importance of optimizing new processes.

<sup>24</sup> These projects must of course be compared to the production capacity of major petrochemical intermediates. Buffenoir (2007) estimates that current production plants produce around 1.7 million metric tonnes / year of ethylene. Technip’s expansion in Russia increased ethylene capacity by 400,000 t, while Linde recently secured a contract in India, which, according to Linde officials, will be part of a petrochemical complex that will produce 1.1 million tonnes of ethylene, 400,000 tonnes of propylene, 150,000 tonnes of benzene and 115,000 tonnes of butadiene per year. The only important announcement we have seen from agro-resources came from Brazilian petrochemical company Braskem, with polyethylene and polypropylene from sugar cane, and an industrial scale production plant producing green polyethylene with a capacity of 200,000 t / year, with construction beginning in August 2010.

methanol from biomass as well as coal gas or even petroleum residues remains valid. But we must be able to identify them in terms of development cycle of the rational myth and disappointments (it seems that in the gasification process, we run up against barriers in terms of gas purification).

Similarly, the avenue of microalgae is another “world of production” which, since early 2009, has been experiencing an unprecedented rise in popularity. Oil companies see in micro-algae a chance to escape the pressure of biomass suppliers by launching their own “above ground” productions; other actors mentioned above are expressing signs of interest, while they continue to explore the cereal biorefinery avenue. Still, this is again a rational myth: A recent press release from Alcimed (March 30, 2009) emphasized that the technical problems (extracting oil from algae is not perfected) and environmental factors are far from resolved for microalgae. The technological expectations from “bioalgae” expressed today (production of hydrogen, biofuels or biogas) will require a great deal more research and development. *“The industrialization of energy from microalgae can be done only if many skills work together to remove existing barriers: genetic engineering, phycology, biochemistry, petrochemistry. There are few global experts and the expertise tends to be dispersed. In Europe, strong collaborations between industry and researchers from these different areas are needed, as in the United States, to participate in the green gold rush,”* the press released concluded. This perfectly illustrates the need to learn and commit to the construction of community patrimonies, and therefore the need to document them.

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