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Towards a new socio-technical regime in bio-sourced chemistry and biorefinery

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Summary

In the chemical industry, the transition to the new socio-technical regime is seen in terms of substituting fossil fuels by biomass, thanks to the technological promises of breakthrough innovations in biorefinery. But the new biotech or thermochemical chemistry's innovations tend to imagine the biorefinery concept as an hybrid system. It is probably more of a transition technology, than the new socio-technical regime itself; it can be magined as a strategic tool to guide the system of environmental innovations in ways that ensure the reproduction of economic stakeholders.

1. Introduction

Today, chemistry is undergoing drastic reorganising, faced as it is with peak-oil on the one hand and on the other hand a lot of questioning arises from both environmental and public health concerns [2] [3]. This article addresses the transition towards the use of biomass. "Biorefinery" appears as an intermediary object[4] around which this very transition is knitted (cf. a short bibliography in the appendix).

One such occurrence is available, which can be documented upon in order to set forth arguments in favour of either weak sustainability or strong sustainability. The discrepancy between "weak" and "strong" lies mainly in that: what opportunities of technical innovation for resource substitutability may offer. According to existing literature, not enough empirical research has been carried out on these debates.[5]

Observations of this kind are all the more necessary as evolutionist economic models [6] were not devised in the first place with a view of tackling the environmental issue but rather of focusing on technological selection from the single point of view of the market efficiency of innovation.[7] [8]

1 We thank Pierre van Zyl and Alain Aitou for their comments.

2 Bernadette Bensaude-Vincent & Jonathan Simon (2008) *Chemistry, The Impure Science*, London, Imperial College Press, 268 p., Bernadette Bensaude-Vincent (2005) *Faut-il avoir peur de la chimie ?* Seuil.

3 Stefan Boschen · Dieter Lenoir · Martin Scheringer, (2003) "Sustainable chemistry: starting points and prospects", *Naturwissenschaften* (2003) 90:93–102, DOI 10.1007/s00114-002-0397-9

4 Vinck D., (2009) "De l'objet intermédiaire à l'objet-frontière. Vers la prise en compte du travail d'équipement", *Revue d'anthropologie des connaissances* 2009/1, Vol. 3, n° 1, p. 51-72.

5 See for e.g. surveys of Ayres (2007) ou Illge & Schwarze (2008) in *Ecological Economics*

6 See e.g. Abernathy (1978) ; David (1992) ; Foray, (1989), Utterback et Suarez, (1993) ; Metcalfe & Miles, (1994)

7 Faber A., Frenken K.(2009) "Models in evolutionary economics and environmental policy: Towards an evolutionary environmental economics", *Technological Forecasting and Social Change*, V. 76, Issue 4, May 2009:462-470

8 Rennings K. (2000), "Redefining innovation – eco-innovation research and the contribution from ecological

These aforesaid models contend that technological development follows a pattern of cycles consisting of two major stages. First, industrial actors seek to explore the whole 'spectrum of possibles', which is revealed by the creation of a wide range of technologies. Secondly, the technological market is prone to selecting a dominant “design” which may result from analysing the relative performances of these various technical solutions or from being “locked-in” on “technological roads” because of the behaviour of dominant actors.

The issue at stake is to know whether the various actors involved in an economy of transition towards renewable resources really wish to see the dynamics of such a model be enacted; namely whether they have sensed it as desirable from the point of view of sustainable development, when its sole base is the economic principle of selecting the most effective technology (according to a dominant actor), and the sole criterion, optimising increasing returns.[9] Such a model banks on the double argument of "*winner-takes-all*" markets and “*one-unique-technological-best-way*” which structured the whole era of industrial productivism.

Our first observations in the field of biorefinery point out to the fact that solutions for substitution are in abundance rather than scarce: one might even claim that there is Hypercompetition between materials and technologies. Each and every one of them raises issues and encounters deadlocks in various compartments – availability, low yield, technologies which are not mastered, and so on. *"Integrating biobased products into the biorefinery faces a tension between “what structures result easily from a given technology?” (i.e., a lack of conversion processes) and “what product should we make?” (i.e., an overabundance of targets). Answers to these questions will result from fundamental research in biomass transformation evolving into the best commercial opportunities."* [10] A wealth of solutions at hand does not warrant that one solution is available and acceptable from the point of view of sustainable development: that’s the reason why we coined the concept of “doubly green chemistry”, in order to point out that founding a process on biomass does not entail that it should be “green” in an ecological sense.[11]

2. Our Agenda

In this article the hypothesis of technological convergence is discussed from two points of view in relation with sustainability: firstly on which knowledge base do the biomass processing technologies emerge? And secondly, is it possible to find a convergence towards a dominating design in science literature?

We pay a particular attention to these questions since the biorefinery actors themselves worry about the pressures that the existence of a single design could exert on both resources and territories.

Our analytical framework is developed in s**ection 3**. Three types of literature are being mobilized: (1) sociologists of the technological *transition management*[12] suggest that the transition requires systemic change (the changes in the socio-technical regime concern simultaneously technological artefacts, institutional rules and modes of consumption -which we will deal with in

economics", *Ecological Economics,* Vol.32, pp.319-332.

9 Foray Dominique (1997) "The dynamic implications of increasing returns: Technological change and path dependent inefficiency" *International Journal of Industrial Organization*, Vol. 15, Issue 6, October 1997, p.733-752

10 Bozell & Pertersen (2010) "Technology development for the production of biobased products from biorefinery carbohydrates- the US Department of Energy's Top 10 revisited" *Green Chem.*, 2010, 12, 539–554:551

11 Nieddu Martino, Estelle Garnier, Christophe Bliard (forthcomming, 2010), "L’émergence d’une chimie doublement verte, une approche en termes de démarche narrative" *Revue d'Economie Industrielle.*
and Nieddu, M. (dir.) *"An Economic Approach to the Integration of Socio-Economic and Technological Dimensions into Research Programmes in Doubly Green Chemistry"* ANR project (2009-2013) - in the program "chemistry and processes for sustainable devlopment (CPDD)

12 Geels, F.W., (2005) *Technological Transitions and Systems Innovations: A Co-evolutionary and Socio-technical Analysis*. Edward Elgar, Cheltenham.

the broad sense of final consumption and intermediate productive consumption within the chemistry industry-; (2) economists of the *sectoral systems of innovation and production* mainly study in the "*knowledge bases*" which define the specificity of sectoral borders and monitor the dynamics of the innovations[13]; (3) *Real Options Approach* broadens its scope from the world of financial choices to technological choices.[14]

That of **Section 4** describes the variety of "knowledge base" such as documented in the scientific publications, using the interdisciplinary research of physico-chemists and biochemists of the CNRS and the INRA and economists of Rheims University (soon to be published [15]). It shows that scientific and technological communities are at loggerheads on how to deal with this "living produce" which is biomass. The strategies of mimicking petrochemistry and the reduction of this "living produce" -and its inherent complexity- into "ordinary basic chemicals" are not the only existing examples. Strategies stemming from intrinsic characteristics of this "living produce" were also identified. These strategies suppose however much more drastic changes -as much in "*knowledge bases*" as in the stages of productive consumption, in the types of end products (e.g. plastics with short lifespan) and in the cognitive roadmap guiding the chemists.

Section 5 uses the "*Real Options Reasoning Approach*" to observe the way in which the economic actors can mobilize diversity resulting from the "*knowledge bases*". It seems quite plain that major companies seek to maintain the variety of existing technological routes.

Section 6 discusses the arguments resulting from two stances:

(1) from an economic standpoint, the strategies of the economic and scientific actors are interpreted and observed from two axes [strategy of pure substitution ***versus*** strategy of searching for functionalities] / [systemic strategy of change ***versus*** modular strategy of change]

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13 Oltra V. and Saint Jean M. (2009), "Sectoral systems of environmental innovation: an application to the French automotive industry", *Technological. Forecasting and Social Change,* Vol.76, Issue 4, May 2009, pp.567-583.
Oltra V. and Saint Jean M., (2005), "The dynamics of environmental innovations: three stylised trajectories of clean technology", *Economics of Innovation and New Technology,* Vol. 14, Issue 3, 2005.
Oltra V. and Saint Jean M., (2005), "Environmental innovation and clean technology: an evolutionary framework", *International Journal of Sustainable Development,* Vol.8, Issue 3, 2005, pp.153-172.
Oltra V., (2008), "Environmental innovation and industrial dynamics: the contributions of evolutionary economics", DIME Working Paper RAL 2.5, n°7 (December 2008) et Cahier du GREThA 2008/28.
Oltra V. and Saint Jean M., (2007), "Incrementalism of environmental innovations *versus* paradigmatic change: a comparative study of the automotive and chemical industries", Cahier du GREThA n°2007-14.

14 Arman Avadikyan & Patrick Llerena, (2009) "Socio-technical transition processes: A real option based reasoning," Working Papers of BETA 2009-21, Bureau d'Economie Théorique et Appliquée, UDS, Strasbourg.

15 Nieddu M., Garnier E., (2008) "Evaluation et changement technologique dans le développement soutenable, le cas des agromatériaux", *Ecole chercheurs thématique CNRS, "L'évaluation de la durabilité", 19 - 24 octobre 2008, Cargèse* , http://www.cnrs.fr/inee/recherche/fichiers/ET_EvalDur_Oct08/MNieddu.pdf
Garnier E., Kurek B., Nieddu M. [2008], "The coordination of the actors in the *"doubly green chemistry" of* Agro-materials", *colloque* "*Biopolymères, Biomatériaux, Chimie Verte"*, La Baule, les 4 & 5 décembre 2008, *https://colloque2.inra.fr/chimie_verte.../O10%20Garnier%20Estelle.pdf*
Garnier (2009) Un cas particulier de recherche de soutenabilité : stratégies d'acteurs autour des agro matériaux (2009), *école chercheurs, CNRS, Cargèse, ANGD – « Quelle place pour la chimie dans une société durable ? »* 19-24 oct 2009, http://www.cnrs.fr/inee/recherche/fichiers/ANGDChimieCargese/E.GarnierCargese10_09.pdf
Nieddu M. (2009) Le vivant doit-il être réduit à de grands intermédiaires chimiques ? E*cole chercheurs, CNRS, Cargèse, ANGD – « Quelle place pour la chimie dans une société durable ? »* 19-24 oct 2009, http://www.cnrs.fr/inee/recherche/fichiers/ANGDChimieCargese/Niedducargese10_09.pdf
Nieddu M. *et alii* (2010) Diversity of Biorefineries and doubly green chemistry: an economic approach, *Lignobiotech ONE Symposium, 1st Symposium on biotechnology applied to lignocelluloses,* Reims, march 28th - april 1st, 2010.
Garnier E., Nieddu M. (2010, forthcoming), « La Mutation génétique d'un mythe rationnel : de la raffinerie du végétal à la révolution de la chimie doublement verte ? », *Colloque de Cerisy, Ethnotechnologie prospective : l'empreinte de la technique, comment les techniques transforment la société*, du 2 au 9 juillet 2009.
Ngomisk A. *et alii* (2010) poster to 18 th European Biomass Conference, Lyon, 3-7 mai 2010
Nieddu M., Garnier E. (2010) "Vers un modèle pluriel de bioraffinerie ?" *BIOFUTUR* 312 • JUILLET-AOÛT 2010, 61-67

(2) from an environmental point of view, the type of innovation in "green chemistry" -in the sense of the twelve principles of Anastas[16] - that each option implies is discussed.

Three paradoxes of the biorefinery
(if one seriously takes into consideration sustainable development)

The first paradox is the recurring problem of *intensification*, a problem which occurs in both the agricultural- and the chemistry system.[17]. In both cases it is acknowledged that the challenge is to carry out a successful revolution within the two separate branches, as indicated in the “doubly green revolution” term used in agriculture. Rather than leading to a decrease of the pressure on human environment, getting closer to the end of the (cheap) oil era results in seeking a double intensification, both environmental and economic: an increase in agricultural outputs, as in the near future 9 billion people will not only have to feed, but also dressed, transported and provided with objects which are still made from fossil carbon today. All of this will have to be done with the very same agriculture we have today. Tensions in the prices of foodstuffs generated by the beginning of the substitution of gasoline by biofuels and the related problems of pollution and deforestation point out to the difficulties of this process.[18]

For example, the intensification can lead to technologically tempting solutions, but these solutions can sometimes end up causing particular problems of articulation between the domain of food and non-food domains. The tempting idea thus consists in re-using the livestock waste of industrial products, such as that of the industrial production of chickens, for biofuels production. In this technico-economic circuit, biorefinery by-products are redirected towards cattle feed. In this case one can say that humans eat the waste of biorefinery by eating meat.[19] This obviously poses a problem of social acceptability when this technology is visible to the public. According to some sociologists, for deeply culturally anchored anthropological reasons, crossing the non-food barrier has an irreversible character.[20]

B. The second paradox is described by scientists as “biomass recalcitrance” (Himmel et al., 2008)[21]: Biomass is not an amorphous matter. During evolution it has built natural resistances to enzymatic or microbial cracking. Biotechnologies then have great difficulty to provide low cost solutions for biomass treatment, which results in maintaining a discussion of the interest of the physicochemical and thermochemical processes. This probably explains the keeping open of alternative technological routes, which are discussed later.

C. The third paradox is contained within the composition of the name: “bio" "refinery”, which suggests the desire to reduce the changes as much as possible (according to the famous "Di Lampedusa Principle": "**everything must change in order that nothing changes"**): to keep the refinery founded on “bio” carbon. The biorefinery can be directed towards the production of major intermediates founded on the model of petrochemistry: it formats individual technological solutions for each intermediate substitution product.[22] This would therefore avoid modifying the

16 Anastas P.T., Warner J.C. (1998), *Green Chemistry – Theory and practice,* Oxford [England]; New York: Oxford University Press, 135p

17 TECHNOLOGIES CLÉS 2010 (novembre 2006), http://www.industrie.gouv.fr/techno_cles_2010/html/mat_22.html

18 Philip McMichael (2009) The Agrofuels Project at Large, *Critical Sociology* 35(6) 825-839

19 NARASIMHARAO KONDAMUDI *& alii*, (2009) A Green Process for Producing Biodiesel from Feather Meal, J. *Agric. Food Chem.* 2009, 57, 6163–6166 616, DOI:10.1021/jf900140e

20 http://www.cnrs.fr/inee/recherche/fichiers/ANGDChimieCargese/BarbierCargese10_09.pdf

21 Michael E. Himmel, Stephen K. Picataggio (2008) " Our Challenge is to Acquire Deeper Understanding of Biomass Recalcitrance and Conversion", in Himmel M.E. dir. (2008) *Biomass Recalcitrance*, Blackwell Pub. Ltd, (p 1-6)

22 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

existing behaviour in terms of the final product consumption such as on the one hand, in the plastics field[23], and on the other hand preserve the capacities and production logic of industrial agriculture and petrochemistry (while often joining again with intermediaries known before the oil era).[24] [25]
This model however has considerable effects if it is not regulated: in Europe and in the United States it can lead to the creation of a “harbour biorefinery”, which aims at maintaining the activity the existing chemical industry generally located in harbours, and result in pressures on world markets to obtain an undifferentiated raw material from renewable carbon sources.[26] Countries producing renewable carbon (such as Malaysia or Brazil) are led to over-exploitation strategies in order to settle durably in the world competition.

Energy (DOE), by the National Renewable Energy Laboratory, a DOE national Laboratory, August 2004, 76p.)

23 Wolf, O. *et alii* (2005) *Techno-economic feasibility of large-scale production of bio-based polymers in Europe*, European Commission: Technical Report EUR, 22103 EN 256 p.

24 USDA DOE (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

25 Hubbe M.A. (2009) 'Retro-' An emerging prefix,” *BioResources* 4(1), 1-2.

26 Van Haveren, J., Scott E.L., Sanders J. (2008) "Bulk chemicals from biomass", *Biofuels, Bioprod. Bioref.* 2 :41–57

3. Methodological and Analytical Framework

a. Our entry in the problem of technological diversity is focused on the observation of the scientist's role in the transition. The Scientist can be seen as the Hero of the transition, because he has to be a « Builder of Solutions » for a sustainable transition from the era of cheap oil to the era of "*renewables*". In order to show the importance of science as a productive force, European Commission has named "Knowledge-Based Bio-Economy" that what it expects from scientists.[27]
Such an economy needs the intervention of scientists for creating new intersectoral links between agriculture and chemistry.[28] The Scientist must develop research programmes that are specific to their scientific area, but he must also take (1) an holistic view dealing with technological complementarities,[29] economic patterns, and social acceptability (2) a multi-level approach from the molecular level, -application of the principle of atom economy-, to the macro-social level[30] -tensions on the sustainability of biorefineries-.
Our method of observation of the diversity consists in reading the major surveys (critical reviews) in papers written by various scientific communities, and in seeing how the scientist builds this holistic point of view.

Journals that have been examined in search of critical reviews on biorefinery deal with skills of chemistry, biochemistry, catalysis, engineering to chemistry: *Green Chemistry, Biotechnology Advances, Bioresource Technology, Biomass and Bioenergy, Biotechnology for Biofuels, Catalysis Today, Chemical Engineering Research and Design et Chemical Engineering & Technology, Computer Aided Chem. Engineering, Current Opinion in Biotech., J. of Biotechnology, J. of Molecular Catalysis B: Enzymatic, Appl Biochem. and Biotechno, Energy Policy, Enzyme and Microbial Techn., J. of Chem. Techn. and biotech.The J. of Supercritical Fluids,,International Journal of Hydrogen Energy, Process Biochemistry,, J. of Agric. and Food Chemistry, J. of Composite Materials, Renewable and Sustainable Energy Reviews, Trends in Biotech* ; all these skills are necessary for the development of knowledge on biorefinery. We have added journals on sustainable development or environmental issues (*Clean, Environ. Progress, Environ. Sci. and Technol., Journal of industrial Ecology* or *Technological Forecasting & Social Change*).

b. Scientists must be able to think a "Doubly Green Chemistry". From an analytic point of view the question is: How to unite two separate thought strategies? The first one is to create the bodies of knowledge devoted to improve in biomass manufacture. It involves research on pre-treatment technologies, plant fractionation - including biotechnological programmes dealing with "biomass recalcitrance"-, manufacturing via microbial and physico-chemical treatments, functionalization of polymers and so on.[31] [32] [33] The second strategy is to implement the *twelve principles of green chemistry*, for example in focusing on energy savings, in using the principle of atom economy or

27 Aguilar A, Bochereau L, Matthiessen-Guyader L. (2008) "Biotechnology and sustainability: the role of transatlantic cooperation in research and innovation" *Trends Biotechnol*. 2008 Apr;26(4):163-5

28 Sanders J. et al. (2008) "Biorefinery, the bridge between agriculture and chemistry", *5th European Biorefinery Symposium*, 26p.

29 See : Kenneth I. Carlaw and Richard G. Lipsey (2001) "Externalities versus Technological Complementarities: a model of GPT-driven, sustained growth", A Paper to be Presented To The Conference in Honour of the 20th Anniversary of Nelson and Winter's Book An Evolutionary Theory Of Economic Change, Aalborg Denmark, 12-15 June 2001 - a revisited version is available in *Research Policy* Volume 31, Issues 8-9, Dec. 2002, Pages 1305-1315.

30 On the concept of "*macro-social level*" see: *siteresources.worldbank.org/**SOCIAL**ANALYSIS/.../May_17-Gary_Green.ppt*

31 Colonna P. (ed.) (2006*)- La chimie verte*, Lavoisier, Tec & Doc, 532p.

32 Hayes D.J. (2009), "An examination of biorefining processes, catalysts and challenges", *Catalyst Today*, V. 145 (1-2), july 2009, 138-151.

33 Kamm B., et alii, (2006) *Biorefineries, – Biobased Industrial Processes and Products. Status Quo and Future Directions*, Vol. 1 et 2, Wiley-VCH, Weinheim.

solvents substitution.[34] [35] [36]

c. According to certain expectations, Biotechs appear in this context as a solution for achieving Green Chemistry. But all the scientific communities do not agree with these expectations. Our concern in this communication is to understand why scientists put forward a diversity of biorefinery strategies and why we do not observe the exploration to find the "best biorefinery system" and the selection of "one best way". What we can see about the diversity of scientific communities working at exploring paths of transition can also be seen about the diversity of economic strategies that are used for influencing the research agendas.[37]

d. In order to describe this diversity we propose to organize the coming together of three approaches to technological changes as resumed in the table below.

How to study a question of diversity ? diversity or "one best way" ?		
1 Transition-management model (Geels 2005, Kemp (2008) Genus & Coles 2008) **The biorefinery as central artefact of a new socio-technical regime**	**- Multilevel (*niches,* change of socio-technical regimes, change of landscape)** **- and Holistic Approach of the change in all dimensions (technological, consumers behaviors, artefact)**	**1 - Diversity of the positions on the path of transition (1st,2d generation, initiate change? technology for maturity ?)** **2- What is changing ? consumer behaviors ? thinking the production ?**
2. Sectoral systems of innovation (Malerba, 2002 ; Oltra & Saint Jean, 2008-18) **- How doubly green chem innovation emerges in a specific technological regime?**	**- Technological Regime determined by technological opportunities, cumulativeness of innovation[38], market condition and institutional framework**	**-Diversity of strategies to Environmental Innovation** **Can we characterize concrete E.I. in doubly green chemistry as :** **- Incremental ? Radical ? Systemic Innovations ?**
3. Real Options Reasoning Approach (Avadikyan & Llerena, 2009) **Companies are looking for a portfolio of options in order to deal with uncertainty**	**- Strategically, they exploit the flexibility and irreversibilities related investment cycles.** **- They search to introduce disruption solutions, while keeping within the existing systems.**	**- Diversity identified by firms :** **How to spot the logic of formation of the dynamic portfolio of technological options in the case of biorefinery companies**

The 'transition management' model

The analytical process of the *transition management* model puts forward the existence of a diversity of '*niches*'. These niches are protected during the experimentation phase by the technological expectations of the scientific and economic actors. These niches form a "*Patrimoine Collectif*" = Collective Patrimony in the sense of non-market-collective-assets- from which the actors can eventually draw transition solutions.

Highlights from the scientific literature show the variety of scientific projects positioning in this transition cycle (see section 4). Some actors claim their solution to be the best because it allows one to start the transition cycle.[39] Other actors argue that they have the solution for the future in order to both preserve the niche -within which they try to finalize their products- and try to convince public and private investors of the necessity to allocate resources in their field of interest right a way.

34 Clark, J.H. (2007) Green chemistry for the second generation biorefinery - Sustainable chemical manufacturing based on biomass, *Journal of Chem. Techn. and Biotechnology*, 82 (7), pp. 603-609

35 John L. Tucker (2010) Green Chemistry: Cresting a Summit toward Sustainability, *Org. Process Res. Dev.*, 2010, 14 (2), pp 328–331DOI: 10.1021/op9000548

36 Sjöström Jesper (2006), Green chemistry in perspective—models for GC activities and GC policy and knowledge areas *Green Chem.*, 2006, 8, 130 - 137, DOI: 10.1039/b511316d

37 "*The activity of* technological *exploration of a multiplicity of different cognitive fields is generally found to be incremental and path-dependent, as a consequence of bounded rationality and industry-specific trajectories of knowledge accumulation* ". S. Mendonc¸ *Research Policy* 38 (2009) 470–482, p.473

38 Faber, A., Frenken, K. (2009). Models in evolutionary economics and environmental policy. Towards an evolutionary environmental economics. *Technological Forecasting and Social Change* 76(4): 462-470.

39 Roberto Rinaldi and Ferdi Schüth (2009) Acid Hydrolysis of Cellulose as the Entry Point into Biorefinery Schemes, *ChemSusChem* 2009, 2, 1096 – 1107

Moreover, the *management transition* literature emphasizes the systemic character of change. This literature articulates changes in the field of technologies and changes in productive or final consumption patterns. Changing the entire system would be particularly costly. No private actor wants to bear the total cost of systemic change. It is therefore necessary to determine what form of division of labour is being built - e.g. the division of labour through the whole supply chain from raw materials to primary intermediate products, secondary intermediate products, functionalized products and so on-, taking into consideration that each actor seeks to influence this division of labor in order to reduce the cost of change to a few modules that can be controlled.[40]

Sectoral Systems of Innovation and their knowledge bases

The diversity of niches must be interpreted within the framework of the theory of *'sectoral systems of innovation'*.[41] They are based on different scientific and technological communities. All of them make bets on the transition, its rhythm and its direction. Every one of them thus tries to define the bases of the dominant fields of knowledge of the sector and to shape the regime of innovation. This result raises two questions: (1) What is the nature of the *knowledge base* mobilized by every type of actor, and how does it influence the creation of the new technological regime and of the new socio-technical system?[42] [43] (2) The differences between knowledge bases must be documented because these differences will result in different types of *environmental innovations*[44] according to the various possibilities of combination of any of the 12 principles of green chemistry. Therefore it is interesting to study what type of environmental innovations can be produced for each type of considered *knowledge base*?

Reasoning on change in terms of real options

How do the actors take hold of this variety of knowledge bases? The *real options reasoning approach* [45] leads one to consider the way in which the economic and scientific actors behave in situations of uncertainty concerning the characteristics of the new socio-technical regime.

In this case, it is necessary to establish '*decision trees'* in order to follow the way by which they try to maintain the choice options open, and identify the investment choices. These can be investments of *exploration* in industrial pilots or demonstrators (in order to maintain a possible option) or real investments of *exploitation* of an option (which leads to irreversible choices considering the level of necessary investments).[46]

The same reasoning must be carried out at the level of public investments and public policies. In fact, public actors (the European Commission with its technological platforms like SusChem or the DOE in the United States, national states or regions) can contribute by their choices to maintain this

40 For example, changes in the mobility paradigm can be made on the basis of a solution of biofuels –change an element of the system so as to maintain its internal logic – or on the basis of renting out bicycles or cars added on to fast trains and city transport – change the way of using cars -.

41 Malerba F. (2002) “New Challenges For Sectoral Systems of Innovation in Europe”, *DRUID Summer Conference 2002* on Industrial, Copenhagen, Denmark, June 6-8, 2002.

42 Unlike the trend of the sectoral systems of innovation and production, for which the knowledge bases are approached and defined ex post in a relatively large way, as a whole corresponding to a given sector, one tries to differentiate the knowledge bases in the creation of a new activity. These bases are therefore, in a dynamic way, the potential source of different technological paths. This point can only be documented in an empirical way because technologies of different bases can turn out to be combinable when being applied.

43 Anastas P.T., Warner J.C. (1998), *Green Chemistry – Theory and practice,* Oxford University Press, 135p

44 Environmental innovation referees to green chemistry

45 Arman Avadikyan and Patrick Llerena (2010) A real options reasoning approach to hybrid vehicle investments Technological Forecasting and Social Change, Volume 77, Issue 4; May, 2010; Pages 649-661

46 Mary J. Benner, Michael L. Tushman (2003) "Exploitation, exploration and process management", *The Academy of Management review*, 2003, vol. 28, n°2, pp. 238-256

diversity of ways or to bring it to an end.[47]

47 The European Community helps different Scientific Communities that explore contradictory ways of technological development e.g. thermochemical and biochemical technical routes.

4. A Competition within sectoral "knowledge bases"

The technological promises of breakthrough innovations in biotechnology generate high expectations (in the sense of Rosenberg, 1976)[48]. According to SusChem, the "*biotech revolution will yield new generations of products with enhanced properties leading to new applications in many industrial sectors"*, and *"will enable increased eco-efficiency of the industry"*.[49]

The advent of a new socio-technical regime is made plain in other areas such as the co-evolution of institutions, consumer behaviour and artefacts that are pivotal in its implementation (Geels, 2005, op.cit). Should such a plan be applied to the new bio-sourced chemistry, then the biorefinery concept will come forward as the main artefact, in so far as it enables new cross-sectoral linkages between agriculture and chemistry.

4a. A result of our survey : a lasting diversity of biorefineries

One wonders however, if these expectations *vis à vis* the promises of "white biotechnologies" are not too high, as demonstrated by Hopkins *and alii* (2007) for medicinal biotechnology[50]: Biomass is not an amorphous material. Throughout Evolution, plants have built up a natural resistance to enzymatic attacks and microbial degradation -a phenomenon described by some authors as "biomass recalcitrance"- (Himmel et al, 2008)[51]. As a consequence, biotechnologies face very strong difficulties in providing low-cost processing solutions to biomass deconstruction. Until now such adverse conditions have often been addressed by reverting to physicochemical or thermochemical processes of biomass conversion.

One can see on the **pictures** (below) the opposition between two "knowledge bases" and two technological promises : on the one hand biotechnological or biomimetic routes searching to manage the reactions in cell and the Kreps Cycle (**right** : map of the complexity of the cell, and exchanges in the cell that must be controlled in industrial processes and not only in laboratory); on the other hand more classical routes as Acid Hydrolysis or thermochemical routes e.g. using syngas of eighteen century or the Second World War process Fischer-Tropsch (**left**: some of the metallic catalysts that must be controlled to achieve the processes of reforming gas into various products).

Pictures to the 4a

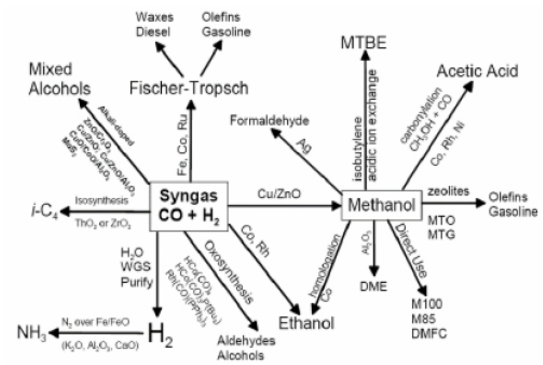
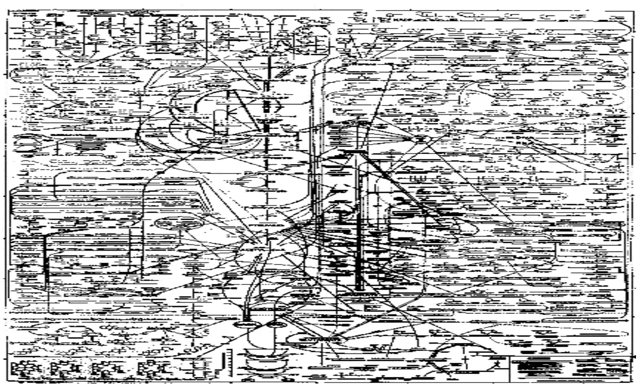


Figure 1: The potential chemicals from syngas and some of the catalysts involved.



48 Nathan Rosenberg (1976) On Technological Expectations, *The Economic Journal*, Vol. 86, No. 343, pp. 523-535

49 SusChem (2010) *A European Technology Platform for Sustainable Chemistry - The vision for 2025 and beyond,* http://www.suschem.org/upl/3/default/doc/38_2170ctp_final.pdf

50 Michael M Hopkins, Paul Martin, Paul Nightingale, Alison Kraft, Surya Mahdi (2007) The myth of the biotech revolution: An assessment of technological, clinical and organisational change" *Research Polic*y (2007) Volume: 36, Issue: 4, Pages: 566-589 ISSN: 00487333, DOI: 10.1016/j.respol.2007.02.013

51 Michael E. Himmel *and alii*, (2007) "Biomass Recalcitrance: Engineering Plants and Enzymes for Biofuels Production" *Science* 9, February 2007: Vol. 315. no. 5813, pp. 804 - 807, DOI: 10.1126/science.1137016

What if technological diversity should last?

Arguments to justify that diversity are: (1) the search for the "right technology at the right time in the right place" (2) the existence of various inhibitors according to the expected end-product.[52]

For example Hayes (2009:148) [53] explains that: *"In summary, it is not currently possible to choose which biomass conversion mechanism is likely to be most cost competitive when commercial operations come online, nor to select which mechanism will ultimately supply the most biofuels or biochemicals. Indeed, it is unlikely that there will be one 'winner'." (...) "Each potential biorefining technology currently has its own drawbacks and advantages and it is likely that a range of procedures will be needed in order to fully exploit the values of very diverse ranges of lignocellulosic feedstocks."*

4b. But there is an another criterion of diversity

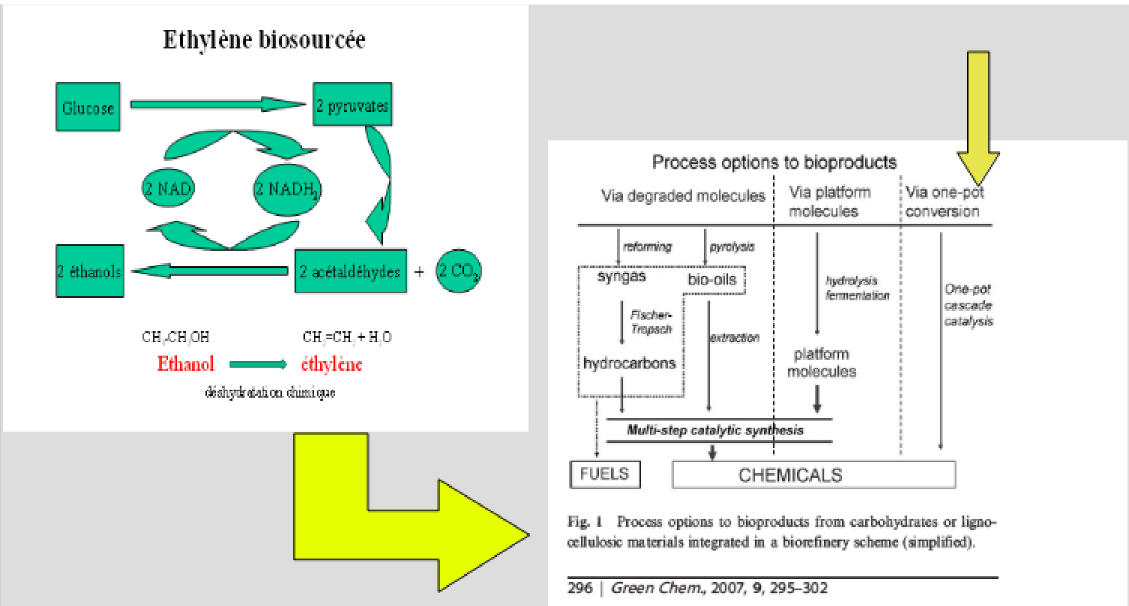
In fact, both thermochemical and biochemical routes are following the same logic. The deconstruction of biomass - (1) within thermochemical process, into simpler "degraded molecules", (2) within biochemical process, into "platform molecules"- was oriented by the same principle : to transform the complexity of living and renewable resources in an agro-industrial product which can be used as intermediate and building-block for conventional use in the present-day chemical industry.

Recent literature shows that another biomass treatment logic seeks to find out more direct routes -without the step of intermediate products, when possible, in order to decrease the biomass conversion cost. This can be done with "one pot cascade catalysis" processes or with limited transformations like in "reactive extrusion" processes.

Pictures to the 4 b: The aspect of productive consumption in socio-technical regimes: Two polar cases ? biosourced routes to fossil oil chemistry or new routes using properties of biomass

left : we can see a reaction using biosourced ethanol as intermediate when going towards major types of ethylene-based polymers of the traditional chemical industry

right : the diagram highlights a "third way": it explores new strategies for biomass conversion to chemicals : One-pot cascade catalysis



By reasoning in the basis of the processes, this diagram shows the diversity of methods in

52 E.g. Roberto Rinaldi and Ferdi Schüth, op.cit.

53 Hayes D.J. (2009), An examination of biorefining processes, catalysts and challenges, *Catalyst Today*, V. 145 (1-2), july 2009, 138-151.

conversion routes. Another type of diversity can be seen in reasoning from the degree of fractionation of raw material, in order to define the intermediate industrial product:

1) The major route is the multistep (re-)synthesis of polymers of interest, from plate-form molecules stemming from the full fractionation (in thermochemistry and biochemistry).

2) Processes as "reactive extrusion" use all parts of the entire plant, such as fibers for the structure, starches for the matrix and so on (Evon, 2008)[54]

3) Another route modifies polymers (e.g. starches into thermoplastic starches) without going through a monomer step (photochemistry or microwave polymers assisted synthesis are used)

5. What can we learn from a "Real Options Approach"?

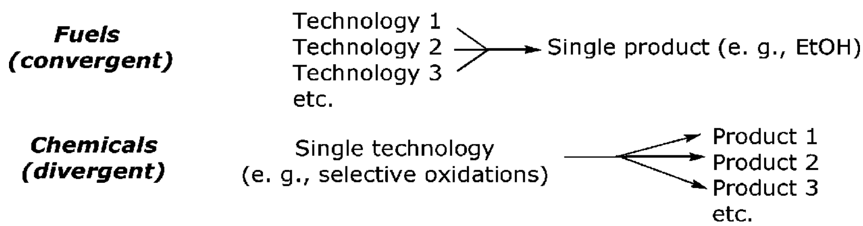
5a. "everything must change so that everything can stay the same..."

Thermochemical and biochemical routes can produce a "fossil-fuel-like" refinery. We called this model an economic model in which « everything must change so that everything can stay the same... » both in the chemical industry and in modes of thought in the research laboratories (see above). This can be seen as a real advantage because this strategy will create a standardisation of the production of versatile semi-products on the one hand, and all learning are oriented in the same direction on the other. American steering committees have designed technological road-maps.

They have identified the "top 30" of bio-based intermediate chemicals, reduced it to a "top 12" in 2004, and they focused on a "top 10" in 2010 (Bozell & Petersen, 2010, op.cit.): Ethanol, Furans, Glycerol and derivates, Biohydrocarbons Isoprene, Lactic acid, Succinic acid, Hydroxypropionic acid/aldehyde, Levulinic acid, Sorbitol, Xylitol.

(extract of Bozell & Petersen *Green Chem.*, 2010, 12, 539–554:540)

Fig. 1 Research approaches for biobased fuels and chemicals.



"Addressing these challenges presents an interesting problem for the integrated biorefinery. As the biorefining industry has expanded over the last ten years, its focus has been almost exclusively on single product operations making fermentation ethanol or biodiesel. Since the molecular structure of the desired output is known, engineering process analysis is ideally suited for determining price targets and identifying technologies that offer the best prospects for research investment.

But when applied to multi-product chemical scenarios, these analysis techniques are less useful because of fundamental differences between fuel and chemical research (Fig. 1). Research in fuels tends to investigate a wide number of different technologies to produce a single or very small number of pre-identified outputs, *i.e.*, biofuels research is *convergent*. If a technology for a fuel process does not meet predetermined cost targets, it is discarded in favor of more economical processes. For biofuels, focus on *product identification* leads the choice of technology.

If chemicals are included as part of the biorefinery's portfolio, the number of possible outputs soars. The experience of the chemical industry shows that this complexity is best handled by using broad-based technologies (selective reductions and oxidations, bond making/breaking processes, catalysis, *etc.*) to produce multiple outputs, *i.e.*, chemical production is *divergent*."

But as it has been previously (see 4b) shown, our survey tends to draw attention to scientific

54 P. Evon, V. Vandenbossche, P.Y. Pontalier, L. Rigal (2010) The Twin-Screw Extrusion Technology, an Original and Powerful Solution for the Biorefineryof Sunflower Whole Plant, 18th European Biomass Conference and Exhibition Biomass, Lyon, 3-7 may 2010

literature that imagines different scientific paradigms and economic models: (1) The choice of the whole plant extrusion ; (2) limited fractionation.

5b. An economic model based on limited starch transformation

Petrochemical materials are known as “statistical”, “amorphous”, “linear” - while starches are “extremely well-structured”, “hyperbranched”, “capable of autostructuration”. One specific pattern is how to functionalize starches while avoiding the phase of "*deconstruction*" into monomers, by using either a mere addition of a reactive agent, or a thermal or mechanical process, or Photochemistry. Photochemistry and photo-crosslinking can be seen as one of historical principles founding the green chemistry (cf. Proti *& alii* 2007).[55]

There are some examples of the use of these technologies, including the production of polymer composites (for exemple Lignostarch programme: lignin adds functional properties to starch materials). How consistent is this approach?

In early 2009, Roquette -a major company which contributes to develop the way of the "fossil-fuel-like" biorefinery- also claims that it returns to functionalize polymers in a programme called Gaïahub. The head of the department research-development of the Italian company Novamont, Catia Bastioli who created "mater-Bi" biodegradable biopolymer, explains the same strategy of portfolio: Besides technical routes to monomers, she presents a research on routes to *"complexed starches"* at the third International Conference on Renewable Resources and Biorefineries (4- 6 June 2007, Ghent-Het Pand)[56].

5c. An economic model based on the whole plant

A Public statement on Vegemat® explains that one can combine the various properties of plant-parts to achieve the end-of-chain product. A one-step process simultaneously uses all the components via extrusion – fibers for the structure of the material, starches and proteins for thermoplastic behaviours of the material, lipids as lubricant agents for the process.[57]

This creates an obligation of changes in consumers' customs and behaviours: short-lived plastics, hemp concrete, functionalised woodfiber insulating materials. How consistent is this approach? In 2008 Dupont bought off one such product from Plantic, an Australia-based company, so as to include it in its portfolio: "Biomax® TPS Renewably Sourced™".[58]

6. Discussion and Conclusion

The biorefinery concept appears as a unified concept, and a sort of guideline for scientists: "integrated industrial complex, zero-waste, diversified" [59]. However, one challenge and thus one demand to scientists was not dealt with in this article: Could the size of biorefineries be adapted to local resources ? Is it possible for small scale local biorefinery and large scale biorefinery units to coexist? [60] [61] And if can small biorefineries can avoid the strategy of setting agrofuels as a priority? Forecasts by different UN agencies (1) note that agrofuels are currently being developed within the

55 Stefano Protti, Daniele Dondi, Maurizio Fagnoni and Angelo Albini (2009) "Assessing photochemistry as a green synthetic method. Carbon–carbon bond forming reactions", *Green Chem.*, 2009, 11, 239 - 249, DOI: 10.1039/b810594d

56 http://www.rrbconference.com/bestanden/downloads/78.pdf, slide 34-35

57 http://www.vegeplast.com/uk/materiau-accueil.html

58 http://www2.dupont.com/Biomax/en_US/assets/downloads/08_0418DuPont_Biomax_TPS_Sheet.pdf

59 See SusChem : http://www.fp7.org.tr/tubitak_content_files//270/ETP/SusChem/SusChem_IAP_final_exec_summary.pdf

60 See for e.g. statements of Eurobioref project : http://eurobioref.org/

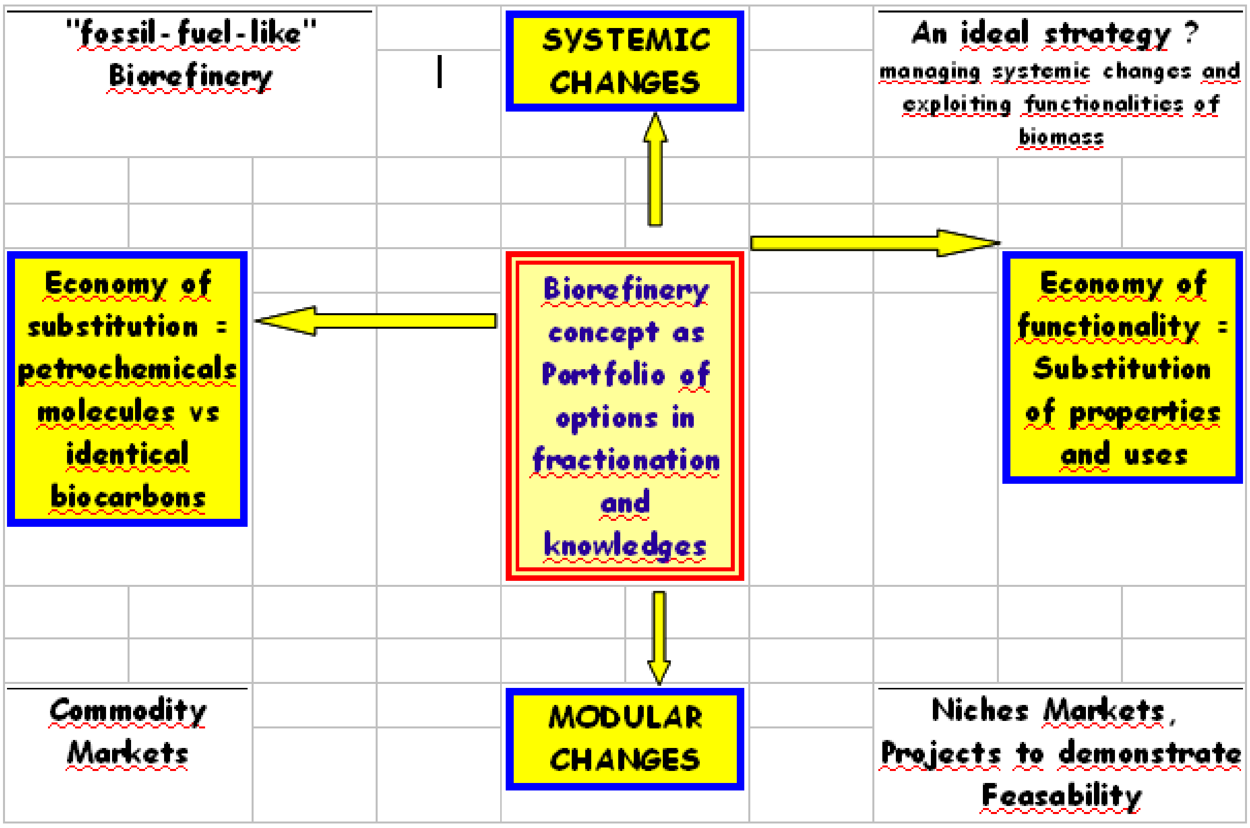
61 See for e.g. statements of the company Novamont *"Novamont biorefinery: a new model of sustainable development integrated with the territory"* (Press Release, Novara, 25th oct. 2006): http://www.novamont.com/detail.asp?c=16&p=1&id=952

intensive, mechanised, agro-industrial paradigm, using massive monoculture and inputs of fertiliser and pesticide; (2) predict that agrofuels lead to further erosion of food sovereignty and food security, threaten local livelihoods, biodiversity, water supplies and increase soil erosion and desertification.[62]

In the study presented here, we have seen that Technological Strategic Choices are the fractionation degree and the predominant combination of science and technical knowledge. Scientists agree that there is no other alternative to replacing fossil carbon in the chemistry of materials, than biobased carbon. In the contrary, in the transport sector other alternatives to fossil fuel than agrofuels may emerge (hydrogen, electricity...). And agriculture alone cannot afford to replace fossil fuels.

In fact, one can analyze actors' behaviors as the outcome of two Strategy Logics: building systemic change *vs* trying to isolate a module which can be changed; substitute a petrochemical product by the same biosourced product *vs* reaching economic functionality via a different renewable product.

Diagramme 1: Economic Strategy Logics in biorefinery (Nieddu, 2009, Training Curse for CNRS' Researchers -Chemistry towards a sustainable society, Cargèse, 2009)



Some authors have pointed out that the identity of the actors who organize the transition significantly impacts the layout of the new sociotechnical regime (Genus & Cole, 2008 [63]; Avadikyan & Llerena, 2009 [64]). Biorefining aims at producing intermediates following the pattern

62 Alice Friedemann (2007) *Peak Soil: Why Cellulosic ethanol and other Biofuels are Not Sustainable and are a Threat to America's National Security,* http://www.energypulse.net/centers/topics/article_list_topic.cfm?wt_id=46 or http://culturechange.org/cms/index.php?option=com_content&task=view&id=107&Itemid=1

63 Audley Genus, Anne-Marie Coles (2008) Rethinking the multi-level perspective of technological transitions, *Research Policy* 37 (2008) 1436–1445

64 Arman Avadikyan & Patrick Llerena, 2009. "Socio-technical transition processes: A real option based reasoning,"

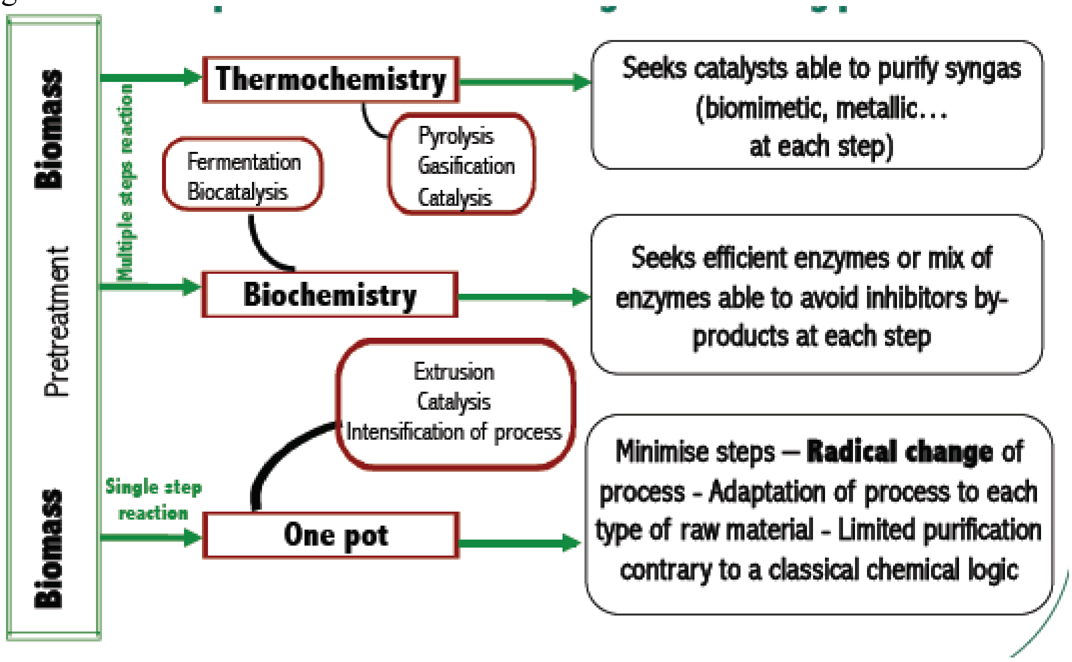
of petrochemistry. Several biorefining strategies technologically substitute petrochemical intermediates, which contributes on the one hand to maintaining current consumer behaviour - such as the use of plastics, and on the other hand, to preserving the capacities and production logics of industrial agriculture and petrochemistry -thus often reviving intermediates, which were used before the cheap-oil era.

In these strategy logics, innovations in the new biotech and bio-sourced chemistry tend to envision the biorefinery concept as a hybrid system: the new bioproduct must be strongly connected to traditional chemical processes. This hybridization enables the relevant industries to cope with the transition to a sustainable society. In other words, one can say that these strategy logics are designed to make sustainable -for these actors- the transition towards sustainability.

Our own observations (Nieddu & al, 2009, Ngomsik and alii, 2010) show how the integration of the 12 principles of Anastas's green chemistry (1998) can be enacted in very different ways. It can be made in a more incremental process along this path to transition, rather than a set of breakthrough innovations. If one observes the use of the principles as *environmental innovation*, one can note that:

- In the case of biorefinery processes based on intermediate molecules, the principles of green chemistry are being applied in the form of incremental innovation, on every step of the value chain.
- While more radical innovations are being investigated in the case of the "minority strategies" e.g. of one-pot processes. Not only must the whole process and the division of labor in the chemical industry change, but also the mode of thinking from the very beginning, by changing the research lab bench working habits: the limited purification in this process runs against the "classical philosophy" of chemistry and engineering.

Diagram 2: Ngomsik and alii (2010) : the ways of "green chemistry" corresponding to the technological choices



The biorefinery policies (and the technological roadmaps of Suschem platform or American DOE) appear probably more like an attempt to manage the beginning of the technology transition

Working Papers of BETA 2009-21, Bureau d'Economie Théorique et Appliquée, UDS, Strasbourg.

than the clear definition of the new sociotechnical regime itself. The biorefinery concept can become a strategic tool used by macro-actors to curb biomass and biorefinery sectoral system of environmental innovation along paths with set a priority of keeping alive present-day economy's stakeholders.

Economic Simulations (Oltra & Saint Jean, 2005) [65] show that an innovative strategy based on a fair balance between environmental and productive dimensions takes more time to develop and needs to address a 'competence destroying effect'. New paths of innovation depend heavily on State Incentives. Government Policies can therefore stimulate the development of innovation paths that tend to reduce biomass to mere intermediate products, or use its inherent complexity to devise new products. The new class of so-called "bioproducts"resulting from one or the other path would lead to very different "biobased worlds"

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