Sustainable chemistry: a new model of Research & Innovation?

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Abstract

Two models of knowledge production can be distinguished in current chemical research and innovation. The first is a "classic" model, which is the natural result of internal transformations in chemical research and industrial activity, in close interaction with their political context. The second is an emerging new model, having different appellations such as "green", "ecological" or "sustainable" chemistry, explicitly driven by environmental concerns.

The first model embodies the "triple helix" theory (Leydesdorff et Etzkowitz, 1996, Etzkowitz et al., 2007), very influent on current research and innovation (R&I) policies in "knowledge-based economies". According to this model, there are three main stakeholders relevant for knowledge production in R&I, i.e., academia, the industry and the government, having equal and partly overlapping roles.

The second model brings, in the knowledge production process, a fourth actor: the civil society. We call this the "tetrahedral model" of research and innovation (R&I) in chemistry. We draw insights on the two models from interviews with 11 researchers in sustainable chemistry in France and we develop the draft of a theoretical approach of the new model in comparison with the "classic" triangular model.

1. Introduction

Contemporary innovation in chemistry is confronted with two major stakes regarding its social viability. The first is related to the difficult and sometimes conflicting relationships between the chemical industry and other components of the society, especially as regards to chemical risks. The negative image of the chemical industry has been found systematically in European surveys.

The second is an echo of the first and refers to how social or regulatory concerns about sustainable development are integrated or not in new research and innovation practices. This is a stake both for the industry and for the chemists in academia.

With regard to the response patterns of the scientific community to this challenge, two models of knowledge production can be presently distinguished:

- a "classic" model, which is the natural result of internal transformations in chemical research and industrial activity, in close interaction with their political context;
- an emerging new model, having different appellations such as "green", "ecological" or "sustainable" chemistry, explicitly driven by environmental concerns.

The emerging model aims at overcoming the incapacity of the classic model to accord to evolutions in the social and political life, but also to new economic constraints imposed by environmental limits on providing resources and absorbing pollutions.

“Sustainable chemistry” is currently an unclear concept, whose content is not consensual. Its meanings cover a range of representations and practices and stretches from a simple marketing argument to a real paradigmatic change in chemical innovation.

The term is mostly used by chemists, who give it a technical meaning related to their discipline but who ignore socio-economic and political components usually related to the term “sustainable”. Anyway, “sustainable chemistry” competes or confounds with other terms like “green chemistry”, “ecological chemistry” or “chemistry for sustainable development” – all suggesting a major reconfiguration in chemical innovation. Which of the different meanings gets imposed is not without consequences for the scientific community, as they can lead to reconfiguration of the funding schemes, open new research pathways and restructure the relationships with the industry.

The most common definition of “green chemistry” refers to new practices in chemical research oriented by twelve principles proposed by Anastas and Warner (1998) (see Box 1). Twelve complementary principles have been defined by Anastas and Zimmerman (2003) for the industrial production, i.e., process conception. All these principles aim at reducing the use of energy and non-renewable resources, reducing the quantity of substances and toxic wastes in the production process, and the reduction of risks posed by the final consumption products.

Box 1. The Twelve Principles of Green Chemistry

(Anastas and Warner, 1998, cited on the website of the American Chemical Society)

1. Prevention

It is better to prevent waste than to treat or clean up waste after it has been created.

2. Atom Economy

Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

3. Less Hazardous Chemical Syntheses

Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. Designing Safer Chemicals

Chemical products should be designed to effect their desired function while minimizing their toxicity.

5. Safer Solvents and Auxiliaries
The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.

6. Design for Energy Efficiency
Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.

7. Use of Renewable Feedstocks
A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

8. Reduce Derivatives
Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.

9. Catalysis
Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

10. Design for Degradation
Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.

11. Real-time analysis for Pollution Prevention
Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

12. Inherently Safer Chemistry for Accident Prevention
Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

Despite clear definition by Anastas and Warner in 1998, the concept of green chemistry seems to have different significations for different people or countries. The analysis of the scientific literature using the term “green chemistry” or “sustainable chemistry” shows that, for certain authors, economic considerations related to costs should be included in the measurement of the “green content” of chemical processes. For others, what makes a process “green” is in itself subject for debate, as for the case of using radiations in chemical transformations.

An important number of articles use “green chemistry” and “sustainable chemistry” as being synonymous and interchangeable and referring to one or at best several principles among the original twelve or 24. For example, for Reznik et al. (2010) the term sustainable chemistry is used by reference to a method for producing surfactants allowing reduction in CO2 emissions associated to raw materials.

For other authors, “green chemistry” and “sustainable chemistry” are different in nature, the last embodying social, political and economic aspects of innovation. For example, for Misono (2009) green chemistry has no meaning for sustainability if it is not socially useful for improving human and environmental well-being. In the same line of thought, Böschen et al. (2003) highlight the social dimension of sustainable chemistry, which would include stakeholder participation in decisions concerning chemical innovation.

Confusion among these two terms seem to be also the result of their history. In 1999 the term “green chemistry” was well accepted and used in Great Britain and United States but not in Germany where it was associated with the green party and therefore to changes perceived as unfavorable for the chemical industry. Consequently, German members of international organizations like IUPAC (International Union of Pure and Applied Chemistry), OECD (Organization for Economic Cooperation and Development) or CEFIC (European Chemical Industry Council) were opposed to its use (Hutzinger, 1999). The term ended by being used both by IUPAC and by, e.g., the Seventh Framework Programme of the European Commission.

In France, the term “green chemistry” has also several meanings. Initially, it has referred essentially to the chemistry of agro-resources (Colonna, 2005), in direct relationship with the agricultural potential of the country. This was an explicit reference to principle 7 of Anastas and Warner (1998) stipulating the use of renewable resources (e.g., vegetal raw materials) instead of non-renewable (i.e., oil) as feedstock. The semantic frontiers currently changed, the “chemistry of agro-resources” being identified through the term “the chemistry of renewable carbon” or “chemistry of plants”. In 2010, the French Ministry of Ecology used the term “green chemistry” to refer to a larger range of sustainability issues in chemical innovation including the chemistry of renewable carbon, the use of white biotechnologies, the management of energy, materials and nanomaterials, chemical engineering and recycling (MEEDDM/CGDD, 2010).

Institutional approaches of sustainability in chemical innovation are equally considering “green” and “sustainable” chemistry as being synonymous, i.e., international organizations like OCDE[1] or research funding structures like ANR[2] (French Research Agency) or DBU (Deutsche Bundesstiftung Umwelt).

Whereas “green chemistry” has a reference definition stemming from original work of Anastas and Warner, there is much less understanding about its social, economic and political dimensions that are determinant for the production and diffusion of innovation. It is therefore important to conceptualize

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[1] http://www.oecd.org/document/6/0,3746,en_2649_34375_1909638_1_1_1_1,00.html

[2] http://www.agence-nationale-recherche.fr/programmes-de-recherche/appel-detail/chimie-durable-industries-innovation-2010/

scientific and technical production of knowledge in chemistry in its socio-economic and political context. In other words, it is important to set the conceptual foundations of the innovation model corresponding to current changes in chemistry oriented by environmental concerns.

In the following, we will start such a work by presenting the triple helix model of innovation promoted in Europe. We critically analyze this model in the light of a small-scale empirical study involving eleven chemists in France and we propose some first conceptual landmarks of a new tetrahedral model of sustainable innovation in chemistry.

2. The triple helix model of innovation

The triple helix of university – industry – government relations is a model proposed by Leydesdorff and Etzkowitz (1996) and focuses on a new role of universities in innovation production and dissemination. This model is actually strongly promoted in "knowledge economies" and has influences on the current restructuring of research and university in Europe.

According to this model, in a "knowledge economy", university, industry and government have equal roles, forming a "triple helix" for boosting innovation. A stable regulatory context is, in this model, necessary but not enough: targeted policies are intended to increase the potential of public research to accomplish some of the research and development previously done in the industry.

The most important change for the academia is a new entrepreneurial role envisaged for increasing its contribution to the economy, with the support of the government. In addition, the industry takes some of the previous role of universities in developing higher education and research. Governments help either at the creation of knowledge-based industries or at their reinforcement (Etzkowitz et al., 2007).

The triple helix model contains three main components:

- a more important role of academia in innovation
- a move towards stronger relationships among the three spheres. Innovation policy is in this context more a result of the interaction among the three spheres, than a governmental prescription or a result of the internal development in the industry.
- in addition to their traditional roles, each of the three spheres "takes the role of the other two". Their action can therefore be described along two axes – a "y" axis of their new role (in the other two spheres) and an "x" axis of their traditional role. Consequently, hybrid structures are created, which bring together elements from different spheres. One example is the "incubator", bringing together elements from academia and elements from the industry. This would be the mean for

academia to participate directly to the creation of new enterprises, instead of having only a role of "support" or "background" in the creation of new companies (Etzkowitz et al., 2007).

The triple helix model can take three forms:

a) the triple helix I, in which the state includes academia and the industry and runs the relationships among them (e.g., China)
b) the triple helix II, which is a "laisser-faire" model, where the government, the industry and academia are separate. Universities provide qualified personnel and knowledge, the companies operate separately from one another in a competitive universe, and the government has a role of "repairing" the "market failures" (e.g., environmental problems) (e.g., United States and Canada)
c) the triple helix III supposes independent but superposing spheres. Academia provides both qualified personnel and research, and creates new companies. The government intervenes in the industry for boosting innovation. Finally, industry participates directly in research and higher education, e.g., through industry-funded professorial chairs. Many countries and regions currently follow this model (Etzkowitz et al., 2007).

Innovation in chemistry has been historically oriented by the three actors considered by the triple helix: the industry, the government and the academic community. Take the example of Nicolas Leblanc and of the founding innovation act of the chemical industry in 1789, the making of pure washing soda, which was then used for the manufacture of cheap soap, textiles, glass and paper (McGrayne, 2001). At the beginning of his career in chemistry he became one of the protégés of the wealthy Duke of Orléans, who maintained a chemistry laboratory together with several young scientists. Leblanc's discovery of washing soda itself was driven by the important prize promised by France's king (Louis XVI), who had the objective to promote the textile industry, and the Royal Academy of Sciences. After he discovered the process of producing washing soda from common salt, Nicolas Leblanc himself was funded by the Duke of Orléans for opening a start-up factory (today, this would be done through a transfer center). Anyway, Leblanc's method has also been extremely polluting, because of hydrogen chloride emission. Lamentably, tens of years passed before regulation managed to partially reduce pollution but the real change has been produced by replacing Leblanc's method with another one, intrinsically less polluting: the Solvay method, more than 100 years after.

Hence, the model of triple helix has been somehow present since the very beginning of chemistry and become even stronger after the Second World War, at the dawn of the current petrochemical era.

The triple helix model is implemented in the chemical sector France through several mechanisms, among which several examples include:

- *Transfer centers* (i.e., regional centers for innovation and technological transfer), allowing easy transposition of research in pilot trial, eventually followed by uptake at industrial scale (MESR, 2012). Such centers have existed in France since the '80s and essentially focused on developing small and medium enterprises.
- *Competitiveness poles*, which are recently created partnerships between industry, research centers and universities identified on a given territory, which are associated to the willingness of the national state to implement an explicit objective of innovation targeting specific markets (e.g., renewable carbon).
- *Carnot Institutes*, including public research structures working in collaboration with the industry with the explicit objective of producing innovation for socio-economic partners.
- *PhD scholarships jointly funded by industry and government*, for students sharing their working time among the two.

3. The sustainability model of innovation in chemistry: insights from a small-scale study in France

In order to analyze the internal dynamics of the scientific community involved in sustainable chemistry and its relationships with politics, economic actors and civil society, we use empirical data obtained from interviews with 11 French academic researchers claiming their affiliation to sustainable chemistry and on a collective book recently published in France on this topic (Maxim, 2011).

We analyze the expression of the "tetrahedral" model in real R&I practices in France and the differences with the triple helix model, along several axes described below.

3.1. Definition and conceptual domain of covered by research in green / sustainable chemistry

Two views were expressed by the scientists interviewed as regards to the meanings of "green", "sustainable" or "ecological" chemistry. For most, green or sustainable chemistry only continues previous work already engaged without such labels. Chemistry based on renewable carbon is the topic the most commonly cited, together with catalysis and processes for environmental clean-up and monitoring.

For one of the researchers interviewed, the terminology depends on the audience: one will speak about "catalysis" to scientists, "sustainable chemistry" in a project proposal and about "green chemistry" when asking funding in a programme focused on green economy. For others, green or sustainable are "politically correct" or simply "political" terms. Thus, several chemists interviewed preferred to talk about "chemistry for sustainable development", which acknowledges the inherent risks of chemistry all by implying some changes in the final use of chemistry as contribution to well-being and implicitly sustainability (e.g., for environmental decontamination and monitoring). However, these changes are not envisaged for the research practices themselves or in the nature of the innovation process. According to this view, chemists always tried to reduce the environmental impacts of their activity as much more when they coincide with cost-reduction objectives (e.g., reduction in the use of energy, of raw materials, of waste…).

For one scientist, “sustainable chemistry” is however a useful term for naming different practices in the research activity of chemists in itself, which are rather prospective than already there in the laboratories. Other two, both having a background in environmental sciences, considered that “green chemistry” is the right term that has to be used as reflection of all the twelve principles of Anastas and Warner, even if their interpretation remains subjective and still devoid of measurable indicators. For the last three scientists, the most important aspect of green or sustainable chemistry is the integration of life-cycle assessments in substance and product research and development.

3.2. Driving forces and constrains for research

The responses of the scientists interviewed about driving forces and constraints for research in green chemistry were rather homogenous. For all, one of the most prominent driving forces for changing innovation in chemistry is chemists’ state of mind and adherence to new responsibilities. Several noted the important role of habits in scientific work. Furthermore, references to green or sustainable chemistry are only starting to be integrated in university programmes and are mostly related to renewable carbon and catalysis, whereas environmental disciplines like life-cycle analysis are still not taught to future chemists.

Research funding can be persuasive for reorienting the research patterns in public research, which could then become a fertile ground of inspiration for the industry. However, the scientists interviewed considered current public funding to be insufficient for really pushing chemistry in the “green” direction. Furthermore, criteria for distinguishing projects really contributing to green or sustainable chemistry are ambiguous, allowing some research teams to develop opportunistic strategies for unduly get funded on “classic” projects all by using “green” vocabulary (“scientific green-washing”). For this reason, all scientists interviewed consider that current research funding is not creating a perennial trend of change in research, even if some are really convinced of the need for a change and consistently work in this direction.

Furthermore, the economy will not change by itself, important political input is needed for getting the results of green innovation competitive, both through stricter taxation and through creation and support to specific markets. As long as the research and the industry are not pushed by regulation and financially motivated to engage collaboration on “green” projects, changes in innovation practices will remain marginal and difficult.

3.3. Research practices, i.e., interdisciplinary collaborations, publication patterns, research funding, etc.

If the collaborations with agronomists for research focused on renewable carbon and with biologists for, e.g., the use of enzymatic processes seem to be common, collaborations with (eco-)toxicologists, risk or life cycle scientists in synthesis chemistry are lacking. Similarly, interdisciplinary collaborations with social scientists in all domains of chemistry remain anecdotic.

3.4. Partnerships between researchers and non-scientific stakeholders: industry, policy-makers and NGOs

Public chemical research and chemical industry are in close relationships. Contracts and collaborative projects are very common, and sometimes joint laboratories.
On the contrary, relationships with NGOs are lacking. Some chemists doubt that their role is to interact with civil society and doubt the scientific competence of NGOs, all by considering international competitiveness as being more important than such societal demands. These scientists feel exclusively responsible for the future of innovation, in which NGOs are regarded as lay intruders expectedly uninformed about the major stakes of chemical innovation and therefore potentially downplaying relevant research and/or national interests. Lay people would have intrinsically contradictory attitudes, because all by taking advantage of chemicals they still don’t “love” chemistry. For this category of scientists, medias have an important role in the negative image of chemistry but chemists could reverse this tendency if they talked more to citizens about what they do and had more pedagogic actions. Anyway, interactions with civil society or with the general public might take time, which can become an important constraint for certain chemists already fully booked.

For others, interactions with NGOs are absolutely necessary for identifying opportunities of risk reduction and because this is a morel obligation of chemists. Indeed, chemistry currently involves enormous social, health and environmental stakes and the public must have the right to contribute to orienting innovation.

The opinions about the responsibility of chemists about the risks of substances they develop are divided. Some consider that policy allowing the marketing of risky substances and technologies or the markets themselves are responsible for chemical risks. Or even that separation between substantive and normative aspects of research is absolute and hence scientists are not at all concerned by chemical risks, which is the responsibility of ethics committees.

For some others, the researcher is responsible but at different degrees. At the higher level, there is the model of the chemist taking the responsibility of envisaging as much as technically possible the risks of the chemicals he/she develops, for example through the use of predictive methods like QSARs or through life cycle analyses.

But some scientists consider that the question should not even be asked because responsibility occurs naturally in chemists due to their status of as citizens and moral individuals. Indeed, these researchers consider that there is a lack of concern and even interest in certain of their colleagues who ignore chemical risks and eventual opportunities to lower them. The reason would be the limited capacities of chemists to act on risks. According to this view, intrinsic properties can be selected by chemists in laboratory in the very step of the synthesis of a molecule, but not exposure, which is the responsibility of the industry and of policy-makers. Thus, the final risk is a more a triangular joint responsibility than a result of the chemists' work.

3.5. Careers of researchers involved in sustainable chemistry and their motivation for working in this domain

For the researchers' careers, "classic" disciplinary orientation remains the most favorable, but promotion of interdisciplinary work related to green chemistry is not discouraged. In addition, specific journals like Green chemistry have an increasing impact factor.

In conclusion, this small-scale interview-based analysis shows well the emergent character of greener practices in chemical research and highlights the division of the chemical community in two camps, one essentially "classical" based on "innovation as usually", and a new one, still a minority, promoting changes in research practices driven by social and environmental concerns.

The criteria making the difference between the two models are:

- The definition given to the "new chemistry"; scientists talk about "green chemistry", "sustainable chemistry", "chemistry for sustainable development", all having different meanings and defining differently the semantic frontiers of the emerging research domain; if some principles among the twelve of the green chemistry are favored (i.e., the use of renewable carbon), some others are ignored (i.e., intrinsic toxicity of new substances, according to the principle "benign by design")

- The disciplines considered relevant for working with chemistry, i.e., agronomy, biology, (eco-)toxicology, social sciences…; indeed some interdisciplinary collaborations (e.g., with agronomy and biology) are easier than others (e.g., with toxicology)
- The relationships between chemists and the general public or NGOs, either directly or through boundary organizations like governmental risk regulation agencies
- The perceived role of the scientific, industrial and risk management policies for orienting research in chemistry
- The relationship between fundamental research oriented by the researchers themselves and applied research oriented by funding agencies and the industry.

Each of this models of dynamics of the research community implies not only specific interactions with the other stakeholders like the government, the industry or the civil society, but also embeds in a specific "socio-scientific complex", having particular social, economic and political characteristics not necessarily directly related to the knowledge production process but which influence it. The socio-scientific complex refers for example to the dynamics of the different sectors of the economy upstream or downstream to the chemical industry (e.g., petrochemical industry, agriculture, automotive industry, etc.) or of other environmental or political stakes like climate change and geostrategic issues. These may influence the price of raw materials, the dynamics of international markets and the economic policies.

4. Why is triple helix inadequate for innovation in sustainable chemistry?

One of the most important critiques made to the triple helix is that it does not take into account social controversies surrounding certain innovations (GMOs, nanotechnologies, etc.). In order to answer these critiques without giving up the metaphor of the triple helix already known by adding a fourth helix, Etkowitz et Zhou (2006) proposed a "double triple helix", which brings together a second triple helix composed of government – university – public. The two triple helixes would function on a ying-yang principle.

Several critiques can be brought to this attempt:

- it is not clear how the two triple helixes interact, in the detail (beyond the "ying-yang" metaphor) and which are the consequences of this new model on the public policies of innovation
- the idea of a double triple helix supposes that there is no interaction between the industry and the public, which is contradicted by current controversies involving NGOs critically highlighting the role of the industry
- the "public" is vaguely identified, and the place of NGOs is not specified

- any specific role is given to environmental regulation in boosting green innovation, despite the fact that risk assessment plays a central role in social controversies about innovation
- more generally, the triple helix gives no role to fundamental research (exclusively public) in innovation and focuses exclusively on industry demand - driven knowledge production. Nevertheless, as long as markets remain competitive there are only low stakes for the industry as regards investments in new areas of research. Short-term strategies driven by markets can downplay long-term developments and favor short-term but not so efficient solutions to urgent problems.

As regards specifically to sustainable chemistry, its new pattern is driven, at least in theory, by social demands for a reduction in chemical risks for health and the environment. However, this change is not easy and interdisciplinarity, which has always been part of chemists' work, encounters new challenges that seem more difficult to overcome. One of the researchers interviewed associated these difficulties to the different perceptions that (eco-)toxicologicsts and chemists have of their own object of work. Chemists often consider environmental demands as constraints for knowledge development or economic progress, whereas green chemistry implies them to be opportunities. This transformation challenges profoundly the researchers' and industry's ways of thinking. More generally, it also challenges the perceptions founding our economic system, the notions of "value" and hence of "markets", "commerce", "consumption"… Change in innovation seems currently driven by restructuring of the relationships between the market and political spheres, and by a new role of regulation for orienting the economic system.

If the REACH regulation currently encourages (eco-)toxicology and chemistry to reinforce their collaboration, scientific and ideological still remain important and difficult to overcome. From a technical point of view, low availability of (eco-)toxicologic data persists whereas predictive methods are still under development. From a ideological point of view, easier exchanges between chemistry and (eco-)toxicology need long-term collaborations that are institutionally, politically and economically viable.

These gaps between research communities apparently made for working together show the limits of the triple helix. Favoring tighter collaboration between the industry and the research community is not enough for orienting the innovation towards patterns that are need to overcome path-dependency as those related to sustainability. Put roughly, sustainable chemistry is neither a demand of chemistry scientists nor of the industry. As long as civil society and environmental ministries are not directly involved in innovation, path dependency will always push the results of the triple helix towards marginal and anecdotic instead of radical and largely diffused innovation in sustainable chemistry.

6. The sustainability model of innovation in chemistry: theoretical considerations

Based on the insights developed above, we propose a new “Tetrahedral Model” (Fig. 1) having the following characteristics:

1. Four pillars instead of three, civil society being the fourth one, playing a role in the decisions taken about knowledge development and about marketing innovations.
2. The social robustness of innovation and its efficient diffusion are insured by cross-peer review in the “enlarged peer community”: knowledge for innovation (including about its potential risks and benefits) produced by the industry is peer-reviewed by NGOs and public scientists, knowledge produced by public scientists is peer-reviewed by NGOs and the industry, and knowledge produced by NGOs is peer-reviewed by public scientists and the industry. Governmental boundary organizations (e.g., regulatory or research funding agencies) could serve of interface, organize and guarantee the quality of this enlarged peer-reviewing process before marketing innovations or when launching research funding programmes.
3. Each sphere has as much strong individuality and independency as regards to the other three, as opportunities for superposition and terrains for exchange and encounter with the others. Whereas in the triple helix each of the three actors partially takes the role of the others, in the tetrahedral model each actor reinforces its specificity (i.e., independency as regards to the others) all by interacting with the others at each step of knowledge production and use for innovation. Instead of confounding the roles of different actors in the society, the tetrahedral model proposes a pattern inspired by multi-party political organization in democracies. In the democratic political life parties with different orientations on the left – right axis co-exist and contribute, through their continuous debates, to the quality of the political life. In the innovation process, the best quality of knowledge is insured through interactions between all those involved in producing or using it. Innovation is as much a scientific, economic and political process. Therefore, boosting green innovation must use the best resources of each of these spheres: the best scientific knowledge producing the highest economic performance with the most democratic process. Beyond the forces of the scientific and economic spheres, the tetrahedral model stipulates the capacity of democratic processes to reinforce innovation, whereas the triple helix rather leads to democratic forces being ignored and potentially opposing to innovation in which they did not contribute.
4. Fundamental research, publicly funded, is represented in a balanced manner in chemistry compared to applied research. This can allow development of knowledge on alternative paths as regards to industry-driven knowledge production, and finally solutions available on the short term when unexpected situations arise on the markets (e.g., when regulation formulates new demands from innovation). Furthermore, fundamental research constitutes an important reserve of novelty for applied collaborations with the industry.

5. In the new model aiming at boosting green innovation, risk policies have an equal role as policies for economic, industrial and research development. Furthermore, policy is intended not only at stimulating research and producing innovation, but also at favoring its diffusion. Indeed, even when greener substitutes exist for toxic chemicals, indirect costs (expenditure on additional training programmes, the need to change operating processes, etc.) impede substitution (Ahrens et al., 2006). Policies must influence the markets in such a way that greener substitutes become more competitive than more toxic chemicals. One example is Denmark, having implemented taxes for certain phthalates suspected of having endocrine disrupting properties.

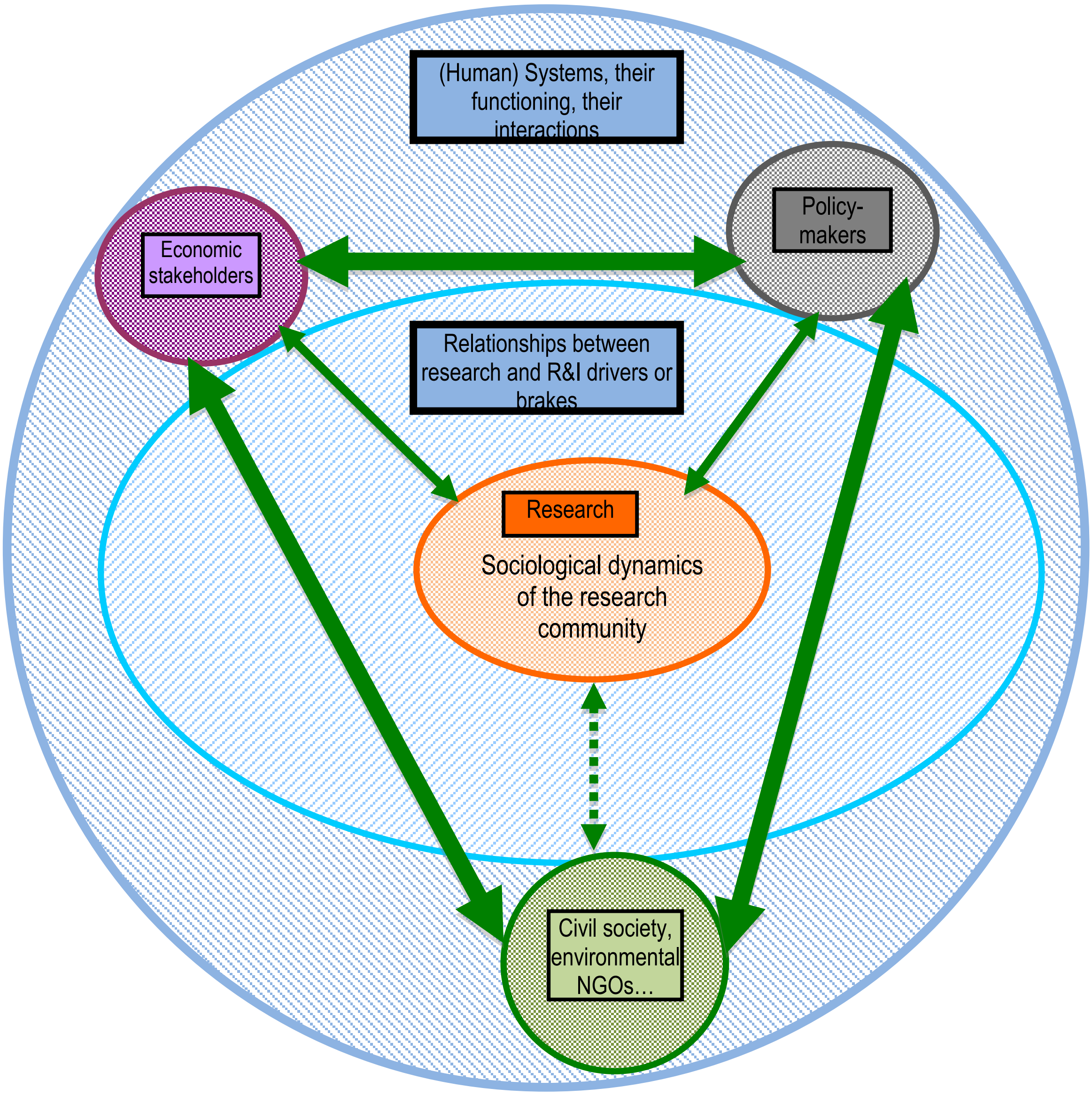

Fig. 1. Analysis layers of the two models of R&I knowledge production in chemistry

Chemists have a new responsibility in sustainable chemistry. Indeed, "classical" chemical synthesis targets two criteria: the use of the substance to be developed and the costs of the future process allowing its industrial production. In this classic model, pollution is managed through "end of pipe" solutions, which render responsible essentially policy-makers for its effective control as an output from the industry. Such management comes in the process as a final step of the research and development:

- just before marketing (i.e., substance authorization procedures) – which creates an important tension between the industry having already invested in that substance and the government having the "bad role" of allowing or not this investment to be rendered efficient through marketing
- through the control of pollution emitted during the production process, which puts financial burden on the state (for monitoring, controlling…)
- at the end of the consumption process, as wastes, which puts financial burden on the public sector again (at different administrative levels).

Sustainable chemistry aims at limiting as much as possible these indirect effects, with conscious intervention during the innovation process itself instead of end-of-pipe solutions. Therefore a third criterion, related to environmental risks, adds to the classical two evoked above for orienting the decisions taken by the chemist in applied research.

According to Van der Sluijs (2002), the extension of the peer community is destined at improving the quality of the knowledge produced in innovation. For the school of post-normal science promoting the idea of extended peer-review, "*quality depends on open dialogue between all those affected".* The "extended peer community" consists *"of all those with a desire to participate in the resolution of the issue. Seen out of context, such a proposal might seem to involve a dilution of the authority of science, and its dragging into the arena of politics. But we are here not talking about the traditional areas of research and industrial development; but about those where issues of quality are crucial, and traditional mechanisms of quality assurance are patently inadequate. Since this context of science is one involving policy, we might see this extension of peer communities as analogous to earlier extensions of franchise in other fields, as allowing workers to form trade unions and women to vote. In all such cases, there were prophecies of doom, which were not realized*" (Funtowicz and Ravetz, http://www.nusap.net/)

The tetrahedral model gives a new role to environmental policies, setting their influence as additional condition for orienting innovation. If the triple helix focuses on economic and research policies aiming at boosting collaboration between academia and the industry, in the tetrahedral model the same is envisaged for environmental policies. Rigid environmental regulations setting clear standards to respect have a positive influence on the development and diffusion of green products and technologies. For the chemical sector, this has been shown by the increase in the number of patents labeled "green chemistry" in United States following reinforcement of the regulation aiming at understanding and managing chemical risks.

The effect of regulation in changing innovation patterns largely depends on the capacities of states to implement the regulation. Such line of argumentation is reinforced by the finding that 70% or more of the companies[3] using dangerous substances do not respect and even do not know the regulation concerning the protection of their workers (Ahrens, *et al*., 2006).

Without specific and targeted support from the state, companies change very slowly or do not change at all. Arduini and Cesaroni (2004) showed that competitive concerns per se do not represent sufficient incentives to favor sustainable innovation. The results of Nameroff et al. (2004) confirm that universities and governmental sector were shown to play the major role in the increase of green chemistry patents in the United States.

Public pressure for adoption of green consumption products is a driving force for innovation in sustainable chemistry (Arduini and Cesaroni, 2004), which can be reinforced through enlarged access to environmental information. Constant regulatory pressure and consumer feedback on innovation through product labeling for reinforcing the use of safer alternatives and other schemes implementing the "right to know" have more sustained effects than discontinuous initiatives (Greenwood and Sachdev, 1999, Ahrens, *et al*., 2006).

In conclusion, the tetrahedral model has three properties distinguishing it from the triple helix and making it apt to create green innovation in chemistry, i.e., a new role of the civil society and the public, a central influence on innovation of the risk / environmental policies and support of economic policies for creating favorable market conditions to substitution, and a new pattern of science-for-policy quality assessment through enlarged peer-review.

All research and innovation processes are embodied in a historically-determined socio-political and economic context, which influences it and which is influenced in return by it. The new model of R&I knowledge production supposes systemic transformations in market functioning, policy-making and social connotations of chemistry. Research aiming at understanding these changes is still very limited and must be engaged.

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