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Assessing the emergence of bioeconomy by the radical technology inquirer tool

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Abstract

This paper reports research results from the application of the Radical Technology Inquirer (RTI) approach on the emergence of bioeconomy as part of the mega wave of socio-technical change that has taken off with the global financial crisis of ca. 2008 and is expected to peak around 2030. The appearance of bioeconomy-related phenomena on this wave was found to be strongly related on the one hand to eight Global Value-Producing Networks (GVNs), and on the other hand on 14 Radical Technological Solutions (RTS). A correlation of these two types of findings reveals an even smaller number of highly promising global value networks (on health, quality of life, and governance) and technological breakthroughs (on DNA research, biosensors, and industrial use of GMOs). The latter appear to follow mostly converging technological pathways, with the bio-info convergence pattern playing the dominant role.

Keywords: Bioeconomy, Foresight, Radical technology inquirer, Converging technologies

Introduction and methodology

In order to cope with an increasing global population, rapid depletion of many resources, increasing environmental pressures and climate change, Europe needs to radically change its approach to production, consumption, processing, storage, recycling and disposal of biological resources. The Europe 2020 Strategy recommended bioeconomy as a key element for smart and green growth in Europe. Advancements in bioeconomy research and innovation uptake will allow Europe to improve the management of natural resources and to open new and diversified markets in food and bio-based products [1].

Bioeconomy in need of a roadmap

The term "bioeconomy" includes all industrial and economic sectors that produce, manage and otherwise exploit biological resources and related services, supply or consumer industries, including agriculture and food industry; forestry and wood industry; health and pharmaceutical industry; bioenergy, biofuels and biochemicals; biowaste utilisation; and related economic, environmental and social systems [2, 3].

The term "bioeconomy" was first used in the short title of the 7th European Commission's Framework Programme, Theme 2, "Food, Agriculture and Fisheries, and Biotechnology", i.e., KBBE or else the "Knowledge-Based Bio-Economy." The expression "knowledge-based" is used to focus on the application and critical role of life sciences and technologies and their effects. Bioeconomy is currently included as one of the key priority areas in the European Union's Horizon 2020 research and innovation programme. The term "biobased" is also used (more in the USA) to put the emphasis on the biological origin of the particular feedstock or of other basic inputs [4–6].

Targeting research to roadmap needs

A lot is at stake with the emergence of bioeconomy in both developed and developing economies, facing strategic opportunities and major risks and threats, whereas research, technology and policy constitute key dimensions of the related actions. Developing a bioeconomy in Europe holds a great potential: it can maintain and create sustainable economic growth, prosperity and jobs in rural, coastal and industrial areas, reduce fossil carbon dependence and improve the economic and environmental sustainability of primary production and processing industries [1]. The successful roadmap for implementing sustainable bioeconomy will depend upon new agricultural practices, new industrial technologies, new business models, new social practices (such as sharing economy) and new skill profiles. This complex task

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requires a sense of urgency to move forward timely and mobilise human and other key resources of this procedure, i.e., a true Copernican Revolution. A forward-looking approach is therefore needed [7, 8].

The target of the research work presented here is to initiate a foresight exercise on the emergence of bioeconomy, considered as a fast-approaching mega-wave of deep socio-technical transformation, following the mega-wave of Information and Communication (ICT)--based change. The new wave, we can call "bio-tsunami", is being built by a wide spectrum of converging elements, technologies, and clusters biology, biotechnology, bioengineering, new agriculture, novel foods, health, quality of life, cosmetics, bioenergy, environment, water, sustainability, education, knowledge management, design of smart applications, and more. The bio-tsunami tends to "absorb" selective elements from all those converging elements, thus strengthening its power and enlarging its applications range, as e.g., in bio-informatics [9–11].

The bio-tsunami foresight methodology

The main lesson from the few previous efforts to apply foresight methods in bioeconomy-related exercises, such as the recent ones by OECD and SCAR [12], is that we need to efficiently bypass the limitations from the complex, changing and fuzzy geography of the bioeconomic landscape. Sectoral studies, such as the ones by SCAR [12], and technology-oriented ones, such as the one by OECD [13], inevitably cover only parts of the emergence phenomena, while neglecting other potentially critical sectors and parameters. So, it appears that the mapping of the emerging bioeconomy mega-wave should be among the key deliverables of an appropriate foresight approach that has to be selected and followed.

Radical Technology Inquirer (RTI) approach

The method selected for the foresight of the bioeconomy emergence in this work is the Radical Technology Inquirer (RTI)-based one. Radical Technology Inquirer came into being in 2012 when the Committee for the Future of the Finnish Parliament ("Eduskunta") started to develop a tool to anticipate and evaluate the social impacts of new technologies. Its latest updated version was used in an EU-funded project called European Radical Innovation Breakthrough Inquirer (RIBRI). Both Radical Technology Inquirer and RIBRI are based on systematic study of open data sources in the Internet, evaluations of experts and crowdsourcing. Both approaches integrate two perspectives: the "technology push" and the "market pull". The "technology push" is represented by 100 promising, radical technological solutions or breakthroughs (RTS). The "demand pull" side is represented by 20–25 "Global Value-Producing Networks" (GVNs).

In order to be a Radical Technological Solution that is suitable for the list of 100 most promising technological breakthroughs, the technological solution has to be important for many GVNs or it has to be really crucial for some GVNs [14].

The central target of this approach is to support and orient regions, countries and various kinds of other actors, e.g., policy-makers, companies, looking for technological strengths and opportunities. These actors can benefit from the toolbox of the Radical Technology Inquirer (RTI). In our research, we have assessed the available information on both RTS and GVNs, aiming to isolate those RTI findings most relevant to bioeconomy [14–16].

Global Value-Producing Networks (GVNs)

According to the definition given in the original RTI tool, GVNs are clusters by demand and areas of change that have been created by global mega-trends and affected by the needs of citizens, considered with a 2030-time horizon. They act as the "demand pull" side of sociotechnical change, expected to be met by 2020–2030 technological breakthroughs. In the updated version of the tool (RIBRI), GVNs are considered to be networks of actors connected by relationships that create value [17].

GVN analysis focuses on the areas of highest volatility/potential for change, while taking into account the following aspects and parameters:

- Current situation and its expected new operating model and its savings;
- Maturity of technological development;
- Challenges of the transition period;
- Legal and structural barriers;
- Potential threats of the new technology or sociotechnical system.

There are two important defining features of the GVN. The first is its special global value promise, and the second is its orientation towards the future. The value promise can describe some global need that all human beings share, for example, security-related needs. In such a way, the attribute "sustainable" is connected to the names of many GVNs. The future-orientation of the 20–25 GVNs means that they are evolutionary or revolutionary alternatives to today's value-creating configurations within the coming 20 years [17]. Undoubtedly, they represent the most innovative element of the RTI tool.

Radical Technological Solutions (RTS)

Our main source of information consists of the 100 most promising radical technological solutions or innovation breakthroughs (i.e., the RTS), which might lead to major world-changing products or services, and are expected to be available by 2020, at the latest. This would indicate that the impact of these technologies could be vast by the year 2030. In order to be able to compare technologies with each other, the maturity of these technologies is also considered. The data sources on specific RTS include open internet sources and the information that these sources provide related to recent novel products or inventions, application areas, levels of market development and scientific interest, as well as their connections to the value-producing networks (GVNs), as introduced above.

RTI operating logic

The logic of the tool is to evaluate any emerging technological breakthrough based on the anticipated values of 25 indicators covering the six areas and aspects already mentioned above. These are anticipated impacts on the 20 global value-producing networks, the anticipated maturity of the breakthrough 2020–2030, the scientific promise of breakthrough technologies, breakthrough focused global market R&D activity, (national) competence in the breakthrough, and national access to relevant application areas of the breakthrough. Based on all those 25 indicators, a list of 100 most promising technological breakthroughs is built [14].

According to the RTI approach, the list of the 100 radical technological breakthroughs—further subdivided into 11 classes—acts as the "supply push" of socio-technical changes; it will be through their implementation that we can expect to meet the 2020–2030 key demand clusters expressed in the Global Value-Producing Networks (GVNs)—the other cornerstone of the RTI toolbox that has been created by global mega-trends and the needs of citizens, with a 2030-time horizon.

Comparison with latest version and limitations of the study

What is of crucial importance in the latest version of the tool (RIBRI) is the structuring and interpreting of the results of a systematic horizon scanning made through RTS and GVNs in the context of Multi-Level Perspective (MLP) theoretical framework developed by leading innovation researchers such as Geels and Schot [18]. The MLP conceptualises the evolution of sociotechnical trajectories as a continuous interplay of societal, technical, political and economic developments on three levels: the macro-level landscape, the meso-level regime and the micro-level niches. In the frame of Geels and Schot cited by [19], niche innovations are the main source that implies the replacement of a recent dominant regime with another regime in the "landscape" of the future. In this framework, acceleration of sociotechnical transitions involves three mutually reinforcing processes: increasing momentum of niche innovations; weakening of existing systems; and strengthening exogenous pressures, which when aligned can create windows of opportunity. The resulting socio-technical transitions go beyond the adoption of new technologies and include investment in new infrastructures, establishment of new markets, development of new social preferences and adjustment of user practices.

However, it should be indicated that—although of high importance and topicality of the issue—the analysis of wider implications of bioeconomy emergence in the context of a typology of sociotechnical transition pathways, as provided by Geels and Schot [18], remained beyond the scope of this research.

Results and discussion

Assessment of global value networks

In this part of the research—the detailed steps of which are reported elsewhere [8]—we have employed the first tool of the RTI methodology, i.e., the 20 GVNs, from the point of view of our foresight study, i.e., regarding the emergence of a bioeconomy, assumed to take place at the global level. The degree of the bioeconomic relevance of each GVN was expressed on a five-level scale (where + = very low, ++ = low, +++ = moderate, ++++ = high, and +++++ = very high). Other factors which were found to play key roles (e.g., as limiting factors or threats) in the bioeconomic activities of each GVN have been also considered in the analysis [8].

During the assessment, a new—the 21st—GVN covering "*Eco-system functions of economic, social and environmental value*" has been added to the list in order to cover an apparent gap in the value chains spectrum, which became particularly evident by the focus of this study on the emerging bioeconomy aspects. This is a clear indication that the present application of the RTI methodology could contribute to its improvement.

The results of the assessment show that, when considering bioeconomic value-based demand factors, the GVN landscape appears to consist of three statistically separate types of structural elements:

- Eight networks represent what we can call the "heart" or the "hard core" of bioeconomic value chains; combined together, they cover ca. 60% of the total weight of the bioeconomic value relevance;
- Eight networks represent the "soft layer" and/or additional and complementary but important value-making systems of bioeconomic nature; together, they cover slightly more than 30% of the total weight of the bioeconomic value relevance; and, finally,
- Five networks represent peripheral and/or loosely related elements to our core and its additional value-making mechanisms; together, they cover less than 10% of the total weight of the bioeconomic value relevance.

The results of the above GVNs assessment can be employed in tentatively mapping the geography of the demand-driving, bioeconomy-based socio-technical change, as follows (the numbers of the networks are the original ones as defined and used in the RTI work) [8, 14].

The Hard Core of Bioeconomic Demand

It includes eight (8) value-making networks:

Bioeconomy-linked GVNs (*CODED)—Brief explanation*

No 05 Local or functional food (FOOD)—A key component of the agro/nutrition//industrial bioeconomic vectors

No 08 Self-care based and personalised health care (HEALTH)—A key component of bio/medical functions of bioeconomy

No 09 New capabilities for those who have lost their functional health (LIFE)—Life supporting systems and quality of life aspects

No 11 Functional materials and new material technologies (MATERIALS)—Novel biomaterials with optimal functional properties

No 12 Functional added value of intelligent goods (GOODS)—Other bioproducts designed to meet specific market niches with novel services

No 13 Sustainable energy technologies (ENERGY)—Bioenergy and biofuels produced and used in a sustainable mode, well integrated in energy markets and grids

No 18 Operation models for self-organising communities (GOVERNANCE)—Need for novel, participatory and decentralised bioeconomic organisations and their management.

No 21 Ecosystem functions of economic, social and environmental value (ECO-SYSTEMS)—Preserving existing ecosystem functions and offering new ones by appropriate bioeconomic developments.

The soft layer of bioeconomic demand

It also includes eight (8) value-making chains/networks:

Bioeconomy-linked GVNs	*CODED*
No 01 Automation of passenger vehicle traffic	HUMAN TRANSPORT
No 02 Automation of commodity transport	PRODUCT TRANSPORT
No 03 Manufacturing close to customers	MANUFACTURING
No 07 Individualisation of learning and guidance	LEARNING
No 10 Equipment for awareness of the environment	AWARENESS
No 15 Participatory entertainment, culture and influence	PARTICIPATION
No 17 Functionalization of spaces and structures	SMART SPACE
No 20 Democracy, freedom and social cohesion	SOCIAL INTEGRATION

The periphery of bioeconomic demand

It includes five (5) value-making chains/networks:

BIOECONOMY-LINKED GVPNs	*CODED*
No 04 Virtualisation of retail trade and services	VIRTUAL SERVICES
No 06 Distance presence and remote control of tools	DISTANT TOOLS
No 14 Raw materials from untapped areas and space	RESOURCE PRESSURE
No 16 National defence and anti-terrorism	WAR AND PEACE
No 19 Virtualisation of identities and social structures	VIRTUAL SOCIETY

Mapping the geography of the bioeconomic value-based demand

In Fig. 1, we use the results of the previous analysis in order to draw a tentative map of the global value-based demand forces driving radical innovation in bioeconomy. All 21 value-producing networks have been included at this stage.

Assessment of Radical Technological Solutions

In this part of the research, we attempt to assess all the 100 RTS of the RTI methodology from the point of view of our foresight study, i.e., regarding the emergence of a bioeconomy, also assumed to take place at the global level. The degree of the bio-economic relevance of each RTS and RTS group is expressed on a five-level scale (where + = very low, ++ = low, +++ = moderate, ++++ = high, and +++++ = very high). Other factors which are found to play key roles in the emergence of bio-economic activities of each RTS are also included in the analysis.

During the assessment, eleven new technological breakthroughs, listed in the Appendix, and covering bioeconomy-relevant topics not included in the original approach, have been added to the original RTI list in order to cover apparent gaps in the RTI-composed technological spectrum, which became particularly evident by the focus of this study on the emerging bioeconomy aspects. More specifically, we have added one new technological solution to each of the eleven classes of the original RTI approach; of these, only one, i.e., that added to the RTS-01 class, was found to play a key role in the emergence of bioeconomy (see RTS no. 13 in Table 3).

Assessment of technology groups

The eleven classes of the 100 + 10 technology breakthroughs of the RTI approach are shown in Table 1, whereas the results of the assessment of the RTS classes are summarised in Table 2.

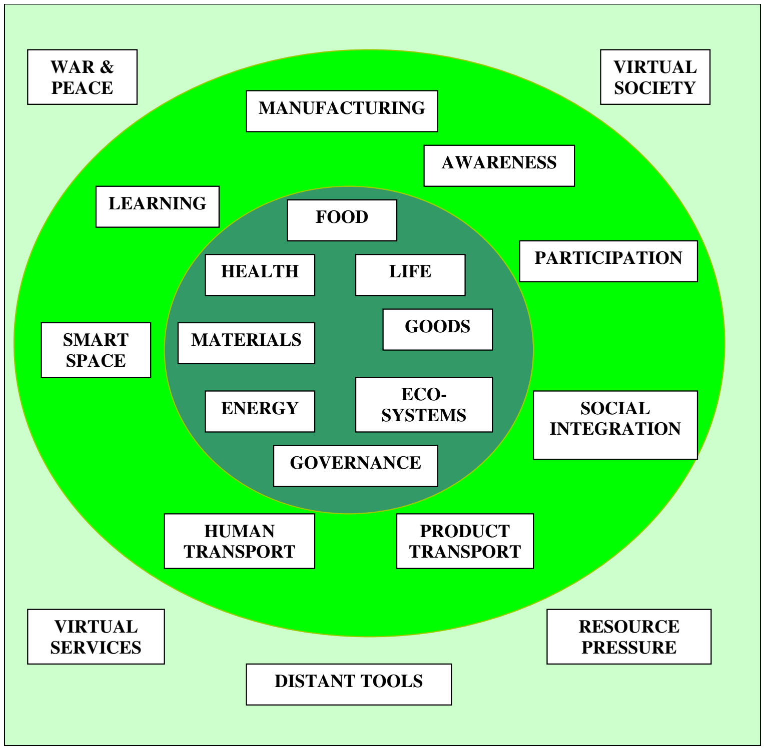

Fig. 1 A dynamic map of the demand forces for socio-technical change affecting the emergence of bioeconomy, driven by relevant global value chains and networks. The inner, dark green circle contains the Hard Core of Bioeconomic Demand GVNs, as defined in the text; the intermediate, bright green circle contains the Peripheral Bioeconomic Demand GVNs (see text); and the outer, light green circle contains the Peripheral Bioeconomic Demand GVNs (see above). Source: [8]

Based on their assessment, and the findings in Tables 2 and 3, the 110 RTS were re-arranged in three new groups, (a), (b) and (c), according to their relevance to bioeconomy. A comparison of the relative weights of the so distinguished three sets shows that, on a relevance score scale 1–5, corresponding to the number of crosses obtained by each RTS.

– Group (a) has 58% of the total relevance: 51 RTS with a total relevance score of 195 (avg. 4.0)
– Group (b) has 29% of the total relevance: 32 RTS with a total relevance score of 96 (avg. 3.0)
– Group (c) has 13% of the total relevance: 27 RTS with a total relevance score of 44 (avg. 2.0)
– Overall: The overall list has 100% of total relevance: 110 RTS with a global score of 335 (avg. 3.0)

Table 1 Classes of Radical Technological Solutions according to the RTI approach

(RTS-01)	Control of metabolism of human beings and other organisms
(RTS-02)	Social innovations
(RTS-03)	Human-machine interface technologies
(RTS-04)	Algorithms and systemic solutions based on the information technology
(RTS-05)	Measuring and imaging
(RTS-06)	Movement and transportation
(RTS-07)	Robots
(RTS-08)	Mimicking of nature and cyborgs
(RTS-09)	Essential enabling materials and industrial raw materials
(RTS-10)	Energy technology
(RTS-11)	Messaging technologies and protocols

Source: [14]

Table 2 Assessment of the RTS groups regarding their bioeconomy relevance

RTS group	RTS classification by relevance indicator					Total RTS in group	Overall RTS group effect[a]
	Very low	Low	Moderate	High	Very high		
RTS-01	–	–	1	4	7	12	4.5
RTS-02	3	7	–	–	–	10	1.7
RTS-03	4	4	–	–	–	8	1.5
RTS-04	–	–	5	5	1	11	3.6
RTS-05	–	2	–	5	1	8	3.6
RTS-06	4	4	–	1	–	9	2.0
RTS-07	2	3	3	2	1	11	2.7
RTS-08	–	–	3	4	2	9	3.9
RTS-09	–	1	3	6	1	11	3.5
RTS-10	1	2	6	4	1	14	3.1
RTS-11	–	–	6	1	–	7	3.1
TOTALS	14	23	27	32	14	110	3.1
RTS effect intensity[b]	0.6	1.0	1.2	1.5	0.6	1.0	

[a]Estimated as the average relevance indicator of each group, with max = 5 and min = 0
[b]Average effect of each indicator class, estimated by the RTS number divided by 110/5 = 22, with max = 5 and min = 0
Source: [8]

The conclusion here is that we cannot neglect the role of the set of medium relevance RTS groups, as together the higher-relevance (a + b) RTS groups reach a score of 87%, leaving for the set of low relevance RTS groups the remaining 13%, which of course is not at all negligible, but for practical reasons can be considered as such in most research cases.

Assessment of individual technologies

Analysis of the available RTI information at the level of individual RTS—the details of which are reported elsewhere [7]—reveals the action of 14 highly relevant RTS, 12 of which belong to the highly relevant RTS group (a), as defined above, with the other 2 technologies belonging to the above defined group (b). The following Table 3 demonstrates the characteristics of the so identified 14 technological "protagonists," including the following two features of technological promise and maturity, as used in the original RTI approach, and defined as follows [14]:

Promise: Four classes of RTS are distinguished, shown by stars: **** for RTS ranked in the top 25, *** for RTS in the second 25, ** for RTS in the third 25, and * for RTS in the bottom 25.

Maturity: The RTS are categorised into four levels of maturity:

1. Scientific principles that make the technological breakthrough possible are proved and the functionality is demonstrated in a peer-refereed scientific paper;
2. Prototype that is scientifically or commercially demonstrated; the functionality of the prototype fulfils requirements of the commercialization;
3. Enough actors that have financial resources develop the technological breakthrough that is close to commercialization; and
4. Increasing amounts of products are delivered to customers, new application areas emerge, and prices of the products decrease.

The heart of this assessment is based on the relevance and applicability parameters, and their resulting relevance indicator; this part of the work draws heavily from the long experiences of the research group of the Bioresource Technology Unit run by the first author at the National Technical University of Athens since the mid-1980s.

As for the impact on value networks parameter, this is based on the original RTI publication [14].

N.B. The above proposed new "geography" of the emerging bioeconomy technological landscape covers only the identified 14 technological "protagonists" and has to be confirmed by follow up studies of the socio-technical dynamics of change.

Assessment of GVNs vs. RTS compatibility—converging technologies

As a final step of our analysis, we attempted to correlate the above presented two types of findings—i.e., those related to GVNs and RTS, respectively—as shown in the following Table 4. From this tabulation, we can easily identify further useful findings regarding the emergence

Table 3 Radical technological "protagonists" of the bioeconomy emergence [8, 14]

No. of RTS	RTS (RTI) PROMISE	Relevance and applicability	Relevance indicator	Impact on value networks
	DNA-based			
01	Routine and complete DNA sequencing ****	All sector tools Maturity (4) High market growth	Very high (+++++)	15/21
02	DNA memory *	Bio-info, in/out-bodies Maturity (3) Close to market	Very high (+++++)	10/21
	Biosensors-oriented			
03	Biochips and biosensors to diagnose cheaply and rapidly diseases, physiological states and genetic features of organisms ****	Many sector tools Maturity (4) High market growth	Very high (+++++)	13/21
04	Printed cheap biosensors ****	Health/food/society Maturity (3) Close to market	Very high (+++++)	17/21
	GMO-based			
05	Drugs based on genetically modified organisms ***	Bio/ICT tools Maturity (4) High market growth	Very high (+++++)	9/21
06	Genetically modified organisms as producers of multi-use materials ***	Energy/biomaterials Maturity (3) Close to market	Very high (+++++)	6/21
07	The production of biofuels using enzymes, bacteria or algae **	Feasible/sustainable Maturity (3) Close to market	Very high (+++++)	7/21
	Health/medical oriented			
08	Longer life time and slower ageing processes **	Health/quality-of-life Maturity (2)	Very high (+++++)	9/21
09	Continuously monitored personal health ****	Health/food/quality Maturity (4) High market growth	Very high (+++++)	14/21
10	Repairing and regrowing of human organs, (stem) cell cultivation **	Health/bio-ethics Maturity (2–4) Very high growth	Very high (+++++)	5/21
11	3D printing of organs *	Medical/human tests Maturity (2) Scientific interests	Very high (+++++)	7/21
12	Artificial cell and simulating life on cell level ***	Food/pharma/energy Maturity (2) Scientific interests	Very high (+++++)	11/21
	Brain-functioning			
13	Smart anti-depressant and other behaviour affecting biochemistry	Health/quality-of-life Maturity (4) Very high growth	Very high (+++++)	13/21
14	Simulation and mapping of brain ***	Cognitive/genetics Maturity (2) Emerging uses	Very high (+++++)	14/21

of bioeconomy through the combined effects of those two forces, i.e.,

I. Those technologies having the greatest momentum of socio-economic change, i.e., DNA sequencing, and GMOs applications—marked red in Table 4, followed by biochips and sensors, as well as pharmaceutical and anti-ageing innovations, marked yellow in Table 4;

II. Those demand sectors of the economy and society with the highest value potential as affected by and affecting the range of technological change related to bioeconomy, i.e., Health, Quality of Life, and Governance—all shown in bold in Table 4; and, especially,

III. The heuristic value of the whole exercise, illustrated, e.g., by the applications of sensors in the

Table 4 Assessing the compatibility between key bioeconomic "questions" (identified Global Value-Producing Networks or GVPNs) and "answers" (identified Radical Technological Solutions or RTS) (XXX = high, XX = medium, X = low, 0 = none)

Highest Bioeconomy Relevant RTS	*Highest Bioeconomy Relevant Demand Sectors as GVNs*								
	Food	Health	Life	Materials	Goods	Energy	Governance	Ecosystem	TOTAL Xs/8
DNA sequencing	XXX	XXX	XX	XX	XX	XX	X	XXX	2.3
DNA memory	0	X	X	X	XX	0	X	X	0.9
Biochips to diagnose diseases	X	XXX	XX	X	X	0	XX	XX	1.5
Printed cheap biosensors	X	XXX	XX	XX	XXX	X	X	XX	1.9
Drugs based on GMOs	0	XXX	X	0	0	0	XXX	X	1.0
GMOs to other products	X	X	XX	XXX	XXX	XXX	XXX	X	2.1
Production of biofuels	X	0	0	X	X	XXX	XX	XX	1.3
Longer life slower aging	XXX	XXX	XXX	0	X	0	XXX	X	1.8
Monitoring personal health	X	XXX	XXX	X	X	0	XX	X	1.5
Repair/regrow human organs	0	XXX	X	0	0	0	XXX	X	1.0
3D organs printing	0	XXX	X	X	X	0	XXX	X	1.3
Artificial cells – Life simulation	0	X	X	0	0	0	XX	X	0.6
Smart anti-depressants	0	XXX	XX	0	0	0	XX	0	0.9

health-care sector, and the development of high-tech tools for better governance of health-care systems, their hybrids with quality-of-life ones, and other highly promising socio-technical change areas.

IV. It is worth noting that some of the most presently discussed technological applications, such as the utilisation of biomass in novel biorefineries by various bioprocesses seem to occupy a place of rather limited weight in the list of 14 protagonists (biofuels); this is a clear message that this type of technological solutions could benefit from creative interactions with other technologies, such as GMOs and innovative governance.

V. On the other hand, the significant position of health-related RTS—including cognitive applications—reflects a real situation and is mostly affected by the original listings f GVNs and RTS.

The systematic use of the RTI tools can also throw more light on the mechanisms of a critical aspect for socio-technical change, i.e., that of *converging technologies*. In Table 5, we summarise the results of such an analysis, focusing on the converging technologies involved in the identified 14 technological "protagonists" of the bioeconomy wave. In Table 5, technological breakthroughs come as result of the convergence of on the average 4.5 of the following elements [13, 20, 21]:

1. *Bio*: biological sciences and techniques
2. *Info*: information and communication
3. *Chemo*: chemistry and chemical engineering
4. *Eco*: environmental sciences and technologies
5. *Med*: medical and health-related applications
6. *Nano*: nanoscience and nanotechnologies
7. *Cogno*: cognitive sciences and mind studies

Table 5 The contribution of converging technologies to the emergence of bioeconomy

Radical technological "leaders" of the bioeconomy emergence and their required synergies through converging technologies
(i) DNA-based
DNA sequencing: *bio, info, nano, systems*
DNA memory; *bio, info, nano, cogno, systems*
(ii) Biosensors-oriented
Biochips to diagnose diseases; *bio, info, med, chemo, mat*
Printed cheap biosensors: *bio, info, chemo, mat, agro*
(iii) Bio-based production
Drugs based on GMOs: *bio, info, med, chemo, eco, system*
GMOs producing other products: *bio, info, chemo, eco*
Production of biofuels: *bio, info, energy, chemo, eco*
(iv) Health/ageing-oriented
Longer life slower ageing: *bio, info, med, chemo, eco*
Monitoring personal health: *bio, info, chemo, mat*
Repair/regrow human organs: *bio, info, med, eco*
3D organs printing: *bio, info, chemo, nano, mat, eco*
Artificial cells—life simulation: *bio, info, med, eco*
(v) Brain-functioning
Smart antidepressants*: bio, med, chemo, eco, cogno*
Brain simulation/mapping of brain: *bio, info, cogno*

8. *Mat*: material sciences and engineering
9. *Energy*: energy and fuel technologies and engineering
10. *Agro*: agriculture and food sciences and engineering
11. *Systems*: systems modelling operation and management

An assessment of the convergence chains listed in Table 5 permits an estimation of the % degree of contribution of the converging elements:

- *Bio, Info*: 100%, i.e., the *bio-info* convergence is the dominant form of convergence, as far as the emergence of bioeconomy;
- *Chemo, Eco, Med*: 50%, i.e., the convergence involving one or more of these three elements affects one of two technological breakthroughs regarding bioeconomy;
- *Nano, Materials, Cogno, Systems*: 25%, i.e., the convergence involving one or more of these four elements affects one in four technological breakthroughs regarding bioeconomy;
- *Energy, Agro, Other*: 10%, i.e., the convergence involving one or more of these elements affects one in ten, e.g., case-specific technological breakthroughs regarding bioeconomy.

Concluding remarks

Assessing the emergence of bioeconomy constitutes an extremely complex task, which requires the creative use of a new toolbox, including a range of analytical, synthetic and forward-looking instruments. As shown in this paper, the approach following the Radical Technology Inquirer (RTI) agenda represents such a valuable toolkit; two specific RTI tools and their interactions as used in our research have unlocked key parts of the emergence mapping story, namely,

- The use of the Global Value Producing Network (GVN) tool has linked bioeconomy with eight global value networks, while also mapping the effects of the other 13 value chains;
- The use of the Radical Technological Solutions (RTS) tool has identified 14 key technological breakthroughs, while also mapping the secondary effects of other 32 technologies, and assessing the roles of other 64 innovation generators;
- A key feature of both RTI tools is their mapping of the whole range of forces for socio-technical change, as secondary factors were sometimes shown to play significant roles;
- The combined use of the GVN and RTS tools makes possible the identification of the most promising "niches" for the growth of bioeconomic applications, including hybridisation trends, e.g., as in bio-informatic technologies;
- The same applies to the constructive use of the concept of converging technologies as a driver of bioeconomic change.

Although the basic orientation of the RTI tools is towards the global dimension, its systematic use in national, regional and even local settings, and their feeding with appropriate data, can lead not only to the development of national, regional and local RTI versions, but also to optimal collaboration schemes, where compatibility will go, hand-in-hand, with complementarity of the partnership. Last but not least, the findings from the use of the RTI tools can provide the basis for other foresight exercises, e.g., those following scenario or cluster approaches, as well as for setting research agendas and for other policy- and decision-making needs.

Appendix

Additional technological breakthroughs

Technological breakthroughs added to the original RTI list for the needs of the assessment (see the "Assessment of Radical Technological Solutions" sectionof the paper for more details):

– Smart anti-depressant and other behaviour affecting biochemistry;
– Web-based voting system for the self-governance of human communities;
– Animal-machine interface technologies;
– Developing biologically based organic computers;
– Imaging and sensing based on bio-fluorescence;
– Self-driven farming and other land management equipment;
– Developing hybrid robot-plant systems for farming applications;
– Growth of plant fibre cells for high-tenacity industrial applications;
– Solving the paradox of lignin utilisation: value from plant polyphenolics;
– Optimising integration of bioenergy and other renewable energies in local/regional systems;
– Sustainable intelligence of machines and humans-machine communication systems.

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