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TECHNOLOGIES OF THE FUTURE – WHAT CAN WE KNOW?

ALTERNATIVE TECHNOLOGICAL PATHWAYS INTO THE 21ST CENTURY

> There is no illusion more dangerous than the belief that the future of science is predictable.
>
> (John Freeman Dyson)

Abstract

Anticipative technological policy making needs technology foresight. The methods used include trend extrapolation, Delphi surveys, and technology demand analysis. It is shown that these methods are implicitly based on certain models of technological development, that they imply specific methodological problems and have their respective forecasting horizons. Specific emphasis is put on the question, how technology demand – arising from environmental or social problems – can be taken into account. The paper concludes with an exercise in “vision assessment” resulting in three speculative scenarios for alternative technological pathways into the 21st century: a “solar path”, a “cybiontic path”, and a “technospheric path”.

1. Technology foresight – an expanding field of research

We live in a period of tremendous technological progress and equally tremendous challenges. New generic technologies exert revolutionary impacts on economy and society, and they by themselves depend on advances in basic research. Governments and enterprises are well aware that science and technology have attained a still growing strategic importance in global competition, and they try to develop and implement specific innovation strategies. But any long-term policy making for science and technology has to be based on assumptions on scientific breakthroughs, on the evolution of technologies and their likely impacts on markets, the chances and risks generated by them, and the options for shaping – or controlling – them.

Technology foresight (TF) is therefore a social necessity, and a growing number of foresight exercises in the US, Europe, Japan and other countries speak of its importance. Anticipation of future developments is not only an academic desideratum but a condition of success in global competition. Paradoxically, the same factors which make foresight a necessity undermine the predictability of the evolution of technology. These factors include:

- shrinking of innovation cycles
- growing synergy of adjacent and even remote technology fields
- increasing interpenetration of basic and applied research
- tremendous costs of research and development
- shifts in public risk perception.

Enterprises and governments are forced by pressure of time and costs to set clear-cut priorities to research. This implies choosing the most promising technologies from a large and not at all clear-cut set of potential emerging technologies. But what are the criteria for selection? Chances and risks have to be identified in advance, which is impossible without a prospective analysis of the socio-cultural environment. Consequently, TF includes a kind of anticipatory technology assessment and is in itself a part of the social process of shaping or creating the future.

According to the OECD definition (Tegart 1999) "Foresight involves systematic attempts to look into the longer-term future of science, technology, the economy, the environment and society with a view to identifying the emerging generic technologies and the underpinning areas of strategic research likely to yield the greatest economic, environmental and social benefits." Technology foresight has to be distinguished from technology forecasting, the methodology or techniques of making predictions – in the words of Burgelman and Maidique (1988, p. 65): "Technological forecasting senses the trends, pressures, and emerging capabilities, interprets them in terms of need, indicates the likely level of support, and forecasts the form of possible innovations and their time scales." Technology forecasting in this sense is part of technology foresight. Most researchers prefer quite generally the term "foresight", since the word "forecasting" nurtures the illusion of making precise predictions of affairs which are unpredictable.

In recent years, TF has become increasingly accepted. Authorities in numerous countries commission – following the example of Japan and the US – TF studies (see table). So did Germany in 1993 with a rather one-to-one translation of a Japanese Delphi survey (BMFT 1993, Cuhls/Kuwahara 1994). The next two generations of the German TF exercise were tailored more closely to national needs and the national research and development landscape (Cuhls et al. 1995 and 1998). In Great Britain emphasis was put less on surveys but on the foresight process, by which TF was integrated in the framework of technological policy making, technology transfer and industrial R&D (Steinmüller 1999a). Other countries – from France and Ireland to Australia, New Zealand and Thailand – came up with their specific national TF programmes (cf. Cameron et al. 1996). Within the Fourth Framework Program the European Union inaugurated an institute devoted to TF – the Institute for Prospective Technological Studies (IPTS) at Seville/Spain – and the European Science and Technology Observatory (ESTO), a network of research institutions involved in technology monitoring, foresight and assessment.

Any TF exercise is implicitly based on assumptions about the emergence, evolution and diffusion of technologies (cf. Huisinga 1996). Into the eighties, the dominating thinking figure was technological determinism. According to this model, the evolution of technology follows autonomous laws and is to a high extent independent of the socio-cultural environment: There is only one "natural" sequence of technologies, an unique linear step-by-step progress. Within this model, the task of TF consists in identifying this sequence, and the task of technological policy making is to accelerate the progress of technology through suitable supporting measures.

With the concept of "social shaping of technology" a change of paradigm took place: The evolution of technology is no longer seen as something independent from social conditions but as a genuinely social process, which takes place under specific economic and organizational constellations and which is – mostly mediated by these constellations – impregnated by socio-cultural factors. Consequently, TF has to explore the present and future socio-cultural, organizational etc. context of technology, and technological policy making has to provide suitable contexts. The most recent concept of "social construction of technology" (Bijker et al. 1987) postulates a "seamless web" of society and technology with a multitude of different actors with different interests from the spheres of politics, economy, research, media etc. interacting in the creation of new technologies. From this point of view, TF is a facet of general futures studies, and technological policy making has to be seen as integral part of general policy-making.

The consequences for the picture, that we can develop for 21st century technologies, are far-reaching. Technological determinism presupposes an unique future of technology, only one evolutionary pathway into the future. But even from a deterministic point of view, predictions are rarely feasible: The prediction of an invention is already half the way to the invention. And new results of basic science are simply out of reach of human anticipation.

If however new technologies result from a socio-technological network of relationships, if technologies can be shaped according to human needs and tailored to fit market demands, the concept of the unique technological future becomes invalid. Alternative technological pathways become conceivable, a vast number of possible technological futures... Which one will be realised depends particularly on normative factors – the interests, wishes, guiding ideas and the strategies of the actors.[1]

2. Methods of technology foresight

TF as a branch of futures studies takes advantage of the futurological tool kit. Principally, explorative and normative techniques are to be distinguished. Explorative techniques are used for identifying possible technological evolutionary pathways; normative techniques are used to find goals (preferable technological pathways) and to target research (defining and implementing programmes). "The aim is less to prophesy than to 'invent' the future, with the focus not on that which might happen but on that which should happen." (Kiefer 1973, p. 947)

The constituting elements of TF methodology are in particular[2]:

- Methods of trend extrapolation, including non-linear procedures (e. g. non-linear regressions, saturation models of growth).
- Procedures that are based on expert judgments ("intuitive techniques"): expert interviews and questionnaires, expert workshops etc. Most prominent among this group are Delphi surveys.
- Technology demand analyses. These normative procedures are used for the identification of possible technical contributions for the solution of ecological or social problems and are mostly also based on expert judgments.

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[1] The paradigm shift in technology evolution models has its counterpart in more recent concepts of technology assessment (TA). TA was for a long time primarily understood as a means of identifying and controlling detrimental effects of a technology after its implementation. Recently, concepts have been elaborated for integrating TA in innovation processes. TA is seen as a factor in shaping emerging technologies – "creative technology assessment" (Hack 1995) and "innovation-oriented TA" (Steinmüller et al. 1999).

[2] Saren and Brownlie (1983) mention as explorative techniques: trend extrapolation, Delphi studies, intuitive forecasts and morphological techniques, as normative techniques: scenarios, relevance trees and conditional demand (analysis of the "conditional demand": Which implications for technology do result from a large project? What are the requirements for achieving a goal of technological policy making?).

TF also makes use of different techniques of technology mapping and technology monitoring, e. g. patent analysis or technology field observation (cf. Boden 1992). But at least for new or emerging technologies empirical data is scarse. Historical analogies and speculations (“genius forecasts”) have therefore to this very day their place in TF (see below). – Which results can we expect from these techniques for technologies of the 21st century?

Trend extrapolation is based on figures. These are at least in part available as a result of technology monitoring: data on the development of performance parameters in a specific field, about the market diffusion of a technology, about cost/performance-ratios etc. An good example is “Moore‘s Law”, formulated by Gordon Moore, the later founder Intel, back in 1965: Computer memory and CPU speed double every 18 months – at roughly constant prices. In spite of a repeated changeover of hardware generation (from vacuum tubes over transistors and integrated circuits to microchips) this rule holds true in quite good approximation to this very day. If one extrapolates Moore’s Law, in 2015 computers (resp. their small successors which may be integrated in almost all technical systems) should surpass the capabilities of today‘s systems by a factor of 1.000, and in 2030 they should be one million times as powerful. – It is not unreasonable to predict that Moore’s Law will not hold another fifty years. Most probably, the miniaturization and speeding of computer components will find physical boundaries in the first half of the century: not even quantum circuits will allow infinitely high information densities. The exponential growth of function parameters will pass into a saturation process – presumably within twenty to thirty years. Trend extrapolation runs here into its forecasting horizon.

However, extrapolation techniques show a more serious deficit: They work only under constant circumstances and cannot take into account discontinuities, ruptures of the trend. Technological breakthroughs or the emergence of new technologies cannot be forecasted by extrapolation methods.

In these cases, TF has to rely on the judgment of experts. The Delphi technique, internationally a standard TF method today, is perhaps the most sophisticated expert-based method. Delphi is a procedure to “obtain the most reliable consensus of opinion of a group of experts... by a series of intensive questionnaires interspersed with controlled opinion feedback.” (Dalkey/Helmer 1963 – in Helmer 1983, p. 135)

At the beginning of a Delphi survey the researchers develop statements (questionnaire items). The questionnaire then is submitted to a panel of experts who independently assess the statements. The responses of this first questionnaire are analysed and the anonymized results are transmitted back to the panelists, who are invited to reassess their opinions in a second set of questionnaires.[3] The advantage of this procedure is that it allows a controlled communication between the panelists without the influence of status or individual sympathies or antipathies between experts.

In TF Delphi studies, the questionnaire items include the evaluation of possible future technologies with regard to their social and economic relevancy, their most probable period of realization, the state of research and development, factors inhibiting research, and possible measures for stimulating research. TF Delphi studies have some advantages: They allow it to address parallelly several fields of technology, and

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3 This process can be reiterated as often as desired, but practical experience with Delphi surveys has shown, that no decisive changes will occur in the third and following rounds.

within the questionnaires explorative items (period of realization) are combined with normative aspects (desirability and possible benefits of a technology). Considering this, TF Delphi surveys can provide useful information and give new impetus to public debates on futures technologies and to technological policy making. Moreover, Delphi studies have achieved a rather good hit and miss record. Such a record was elaborated for the 1971 Japanese survey. We can now ascertain for 530 of the 644 items of the study whether the expert estimations correspond to reality or not. 28% have been fully realized: LCD displays, artificial insulin, worldwide satellite supported weather observation. Another 40% were realized partially at the estimated time. About one third of the expert forecasts did not come true or have been proven unrealistic, e. g. accurate medium- and long-term weather forecasts or international admission standards for pharmaceuticals (Grupp 1995, p. 53). Quite systematically traffic and energy items were misses. The reason can be pinned down to the oil-price shock of 1973, which transformed the energy sector. This example displays an inevitable weakness of Delphi studies: Even the most far-sighted experts can not and / or will not envision sudden political or economical ruptures.

Delphi surveys normally operate with a time-horizon of 15 to 25 years, statements for longer periods – which naturally are more speculative – are usually not submitted to the experts. Since political and other contingencies accumulate for longer timeframes, this restriction is quite reasonable.

The most recent German TF Delphi study (Cuhls et al. 1998) consists of more than 1.000 items in 12 technology fields from space research to new services. Some items follow the lines of traditional quantitative technological progress (magnetic levitation vehicles, thermonuclear fusion reactor), other items are related to the vision of sustainable development (e. g. extremely economical motor vehicles). Although the relevance of environmental aspects is less stressed by the experts than in the 1993 German Delphi survey, questions of climate protection, environmental technologies, sustainable use of energy etc. play an important role.

Delphi studies can be used to derive road maps for a technology field. Disregarding probabilities of realization and taking only the median values for the time of realization, we can establish e. g. for consumer-oriented information and communication technologies the following road map:

2003 Teleshopping with digital money is used by many persons.

2004 An internet of the next generation is realized.

2004 Software agents fulfil routine tasks.

2006 Virtual supermarkets are very common.

2007 Speech recognition is used as common interface technology.

2008 In Germany 30% of daily goods are sold per teleshopping.

2010 Reliable automatic translation is achieved.

2012 Leisure parks in cyberspace attract many people.

Furthermore, by means of the Delphi results comprehensive pictures of application fields can be elaborated. Teleworking is one of the many examples. Between 2005 and 2010, new communication and information technologies will facilitate different kinds of telework arrangements for about one third of the workforce and consequently exert a massive effect on the organisation of companies. “Virtual enterprises”, consisting of a network of collaborating teleworkers, will be one result.

But TF Delphi surveys do not make in-depth studies of emergent technologies pointless. This holds especially true for the identification of social requirements or economical demands for specific technologies: "... it is apparent that the conventional paths of the 'technology push' and the 'demand pull' have to be complemented by a third approach, in which foreseeable developments in the economy, politics and society have to be operationalized in such a way that market potentials are rendered visible, which are oriented towards foreseeable bottlenecks." (König et al. 1996, p. 7)

In the Netherlands technology demand analyses have already some tradition (cf. van der Meulen 1997). Guiding questions for the Dutch TF efforts were in particular: Which new technologies would be able to add significantly to the solution of environmental problems? And which measures must be taken so that the development of environmental technologies is stimulated in the Netherlands?

It remains at least for the time being an open question to what extent the analysis of actual and future technology demands can anticipate the evolution of technology. Anyhow, TF tends generally to be too optimistic in the short run, and it lacks vision in the long run. As a rule, the potentials and impacts of technical innovations are underestimated as well by technical experts and by social researchers.

3. Technology scenarios for the 21st century

TF Delphi surveys provide a close look at hundreds of separate technologies. All these singular technological developments combine to an overall evolution. On this "macro-level" certain generic tendencies for the evolution of technology at the beginning of the 21st century may be discerned:

- Firstly, continuous miniaturization in nearly all technological fields is paralleled by an increasing integration of technical systems at all scales – from microsystems, buildings, computerized cars and industrial plants to communication, power, transport and other networks. Traditional infrastructures are transformed into novel organism-like suprastructures.
- Secondly, information technologies are integrated in all technical systems, making them increasingly "intelligent" and capable of autonomous communication among each other. At the same time, technology becomes "dematerialized" in the sense that the value added of software clearly dominates.
- Thirdly, we observe a continuous integration of life and technology. On the one hand, technical system are constructed according to models from the organic world or following its principles (genetic engineering...), on the other hand, technology penetrates into living systems or is attached to them by techno-organic interfaces.
- Finally, simulation is becoming a fundamental aspect of technology. Simulations are used more and more frequently in research and development. Simulation techniques are widely applied in the fields of media and communication – including virtual realities (or more precisely: environments).

If we want to look into the long-term future of technology, we are forced to rely on historical analogies and on "vision assessment". From the historical point of view it is clear, that technological innovations and economy are strongly interconnected. Here, the model of "long waves" or "Kondratieff cycles" – cycles of the world economy with a period of a little more than fifty years – has proven useful. According to this model, which is fairly well supported by statistics, basic innovations give rise to periods of high growth rates of the world economy. Thus steam power and railways, electrical power, chemistry and automobiles have given a push to their respective growth cycles of the world economy. We are for the time being at the beginning of the fifth period of high growth rates, the fifth Kondratieff cycle, caused by information an communication technologies (cf. Nefiodow 1997). This cycle is supposed to go into its down-slope in about twenty years, followed by the sixth Kondratieff cycle at the middle of the century. Which technologies could give rise to it?

It is a common guesswork among futurists and TF researchers, that life sciences will play an increasingly crucial role in the next decades: from biotechnologies – including genetic engineering and health service technologies – to environmental technologies following biological principles. Perhaps these technologies will be closely connected to another wave of innovations: in the field of cognitive sciences including artificial intelligence, language engineering etc. Therefore, historical analogy could suggest that we will come into a century characterized by life and brain technologies.

But one should be well aware, that longer-term TF remains – due to the intrinsic time horizons of all quantitative and objective methods – a field of speculation. There is no lack of speculations, indeed. Many scientists engaged in either basic research or in R&D activities, came up with visions of the future of their field of research and possible impacts on society, economy and everyday life. To mention only a few examples in the field of robotics and artificial intelligence: US robotic researcher Hans Moravec speculates that advanced robotic systems and artificial intelligences will pick up the evolutionary baton from their human creators and head out into space to colonize the universe (Moravec 1990), the Belgian robotic researcher Luc Steels envisions plug-in-modules for the human brain to enlarge its capabilities, Eric Drexler – founder of the Foresight Institute at Palo Alto/Cal. – imagines a nanotechnological revolution with nano-robots of macromolecular size (Drexler et al. 1991), Vernor Vinge, mathematician at San Diego State University and SF writer, puts the idea forward that artificial intelligences may perfect themselves. This would lead to an increasingly fast technological evolution with a rupture (singularity) around 2030.[4]

Visions like these should not be turned down at first glance as something completely unrealistic or utopian (or anti-humanistic in view of strong ethical objections which can be raised against a "robotization of the human being" or its replacement by artificial intelligences). Visionary ideas of many pioneers – like e. g. K. E. Tsiolkovsky or other pioneers of spaceflight – appeared to their contemporaries very often extremely unrealistic or outright fantastic. Of course, many of them have never and will never be realized, but it is difficult to draw in advance the demarcation line between the possible and the impossible. According to a statistical study of intuitive technological forecasts from the first half of the 20th century only half of the forecasts came true – and a high degree of professional competence did not necessarily result in a better prognostic "hit rate" (Wise 1976).

Apart from high or low "hit rates", the value of speculative forecasting for TF should not be underestimated. Speculative predictions are an expression of the guiding images which are shared by pioneer communities. These guiding images set goals for research, direct R&D activities, foster the coherence of teams and serve as a means

[4] Vinge uses a hyper-exponential trend extrapolation (starting point: Moore's Law) that yields a singularity around 2030. Cf. http://www.aleph.se/Trans/Global. – For the visions and speculations in this paragraph compare also Steinmüller (1999b).

of communication among collaborators with different disciplinary backgrounds (cf. Dierkes et al. 1996).

A theory of the evolution of technology which would allow anticipations is still yet to come, and it remains questionable whether such a theory is at all attainable. Within the framework of the demand and bottleneck driven model of innovation there are however good reasons to assume that in middle and long term socio-cultural factors determine the direction of the evolution of technology. Accordingly, the prerequisite for the success of a specific line of technology in the competition of many theoretically possible or already emerging technologies for economic implementation and social acceptance is that the guiding images of this line achieve cultural predominance.[5] As a consequence, an analysis of competing guiding images can give strong indications about the possible future developmental pathways of technology. Thus, a kind of "vision assessment" can be used to derive not technology forecasts but alternative technology scenarios for the 21st century.[6]

Vision assessment has to start with the identification, collection and systematization of existing guiding images. This can be done by screening futurological papers and books as well as opinions expressed by technological pioneers in different fields. Interestingly enough, the multitude of visions scattered in the literature can be sorted according to the relation of technology and nature. How far will technology transform nature – in the double sense of the organic world around us and of our own human biological nature? Putting the question this way, technological long-term prospects are based not only on technological policy making but – on a less manifest and more fundamental level – on policy decisions with respect to nature.

According to the relation of technology and nature three basic technological evolutionary pathways can be distinguished:

1. Preservative or "solar" path: This scenario is characterized by a strictly preservative – or even restorative – relationship to nature and the environment. Economical and technological policy making follow the principles of ecological, social and cultural sustainability. More welfare is attained despite of decreasing resource exploitation (efficiency revolution in technology combined with a sufficiency revolution in lifestyles – cf. von Weizsäcker et al. 1995). The core item is an economy based on alternative energy sources in particular solar energy (Scheer 1993). The attitude towards human nature is conservative too: Laws and/or ethical barriers protect the human body against a "technological reconstruction".[7]
2. Reconstructive or "cybiontic" path (de Rosnay 1997): Mankind is understanding its aim as "improving" nature. Artificial intelligence, genetic engineering, nanotechnology etc. facilitate an increasing integration and interpenetration of living and technical systems, a general remaking of nature according to human purposes and at least a partial remaking of the human being. Natural environment – which has been destroyed to large parts – is reconstructed techno-organically, a homogeneous biotechnosphere emerges in place of the former biosphere – as bad

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[5] A technology is not socially successful because it is technologically superior but it is regarded as technologically superior because it is socially successful.

[6] The idea of "vision assessment" as a tool of long-term TF scenario construction is presented in Steinmüller (1997). Vision assessment as a branch of technology assessment is described in Grin/Grunwald (2000).

[7] Examples are the German Embryo Protection Law and the European Convention on Bioethics.

substitute for the lost world of creation in one interpretation or a new step in evolution in the eyes of others.

3. Constructive or purely "technospherical" path: In the vision of Moravec (1990) and others, mankind will leave the cradle of nature, detach itself from the organic world and transform itself by that act. Maybe, the human mind is transposed ("downloaded") to another physical substrate or exists independent of physical platform as software. Artificial intelligences colonize space.[8]

It has to be assumed that at least elements of the first two scenarios will be realized. But the competition of technological guiding images for the future is not yet decided. In addition to unexpected technological breakthroughs like e. g. cold nuclear fusion or self-aware artificial intelligence, political and social wild cards prevent any pinpointed forecast. It would be a surprise for the futurist if the first decades of the new century would not come up with surprises.

One can only agree with the authors of the German Delphi surveys: "The methodological finding is now generally accepted that precise forecasts are not possible. The identification and evaluation of future technological developmental lines lie on principle beyond the limits of traditional scientific methods. [...] Nevertheless technology foresight is not worthless. TF provides with all the collected data a rational and comprehensible information base, it offers a sound knowledge for orientation, and it helps different addressees, to trace new and additional possibilities and to give their actions more aim and structure and justification." (Cuhls et al. 1995, p. VII, translated)

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[8] Space travel may have to play a role in all three scenarios although manned space travel over interstellar distances requires a reconstruction of the human being.

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Table: Recent Technology Foresight Exercises

Year	Country	Title
1991	USA	Technology Priorities for Americas Future
1991	USA	Report for the US Office of Science & Technology
1992	Japan	Report of the Year 2010 Commitee
1993	Japan	5th Technology Forecast Survey, Forecast to the Year 2020
1993	Germany	Technologie am Beginn des 21. Jahrhunderts
1993	Germany	Dts. Delphi-Bericht zur Entwicklung von Wissenschaft und Technik
1994	Australia	Matching Science and Technology to Future Needs
1995	Germany	Delphi-Bericht 1995. Mini-Delphi
1995	France	Delphi-France
1995	UK	Technology Foresight Programme
1996	USA	Delphi Forecast of Emerging Technologies
1996	Australia	Developing long-term strategies for science and technology in Australia
1997	Japan	6th Technology Forecast Survey, Future Technology in Japan
1998	Italy	Le priorità nazionali della ricerca industriale
1998	Germany	Delphi ‚98. Studie zur Globalen Entwicklung von Wissenschaft und Technik
1998	Austria	Delphi-Austria
1998	USA	New Forces at Work. US National Critical Technologies Review Group
1998	New Zealand	Foresight Project Blueprint for Change
1999	Spain	Primer Informe de Prospectiva Tecnológica Industrial
2000	Germany	Futur-Prozess

This paper was presented as keynote address to the „Second Global Congress on Engineering Education", Wismar University July 2000. It has been published as "Technologies of the future: What can we know? Alternative technological pathways in the 21st century" in Zenon J. Pudlowski (ed.): Second Global Congress on Engineering Education, Melbourne 2000, pp. 105-110.