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Nanotechnology as General Purpose Technology[*]

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Abstract

Scientific literature postulates that nanotechnology is to be considered as general purpose technology (GPT), characterized by pervasiveness, high technological dynamism and the inducement of innovations within a variety of applications. We set out to not only further systematize existing approaches investigating nanotechnology's GPT traits based on patent applications, but to extend the analysis to academic publication data, in order to cover both knowledge creation and application development. By utilizing well established and consolidated indicators of GPT features, such as generality, diffusion, and forward citation rates, as well as contextualized technological coherence as a new weighted generality measure, we compare nanotechnology's research output to the ones of ICT as accepted GPT and of the combustion engine as a non-GPT, representing an upper and lower benchmark, respectively. Moreover, we add the EU27 as new institutional setting. Our results indicate that while nanotechnology is not as clearly perceptible a GPT as ICT is, the potential to develop as such and hence to become an 'engine of growth' is clearly given.

Keywords: general purpose technology, nanotechnology, patents, publications, generality, technological coherence

JEL-codes: O330, O300, O340

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1 Introduction

Scholars emphasize that nanotechnology is not only one important but the general purpose technology (henceforth GPT) of the coming decade. Nanotechnology's versatile and interdisciplinary nature combines all classic basis technologies, promising revolutionary alterations of mankind's life, work, and perception of reality at all levels. GPT's sustainable economic surplus is created by the pervasive mutual inducements and complementarities of joint inventions in GPT and application sectors, yielding wide, continuously self-enhancing and accelerating impacts for the entire economy during whole eras (Bresnahan 2010). There is a vast literature examining whether past technologies are to be called a GPT, e.g. Lipsey et al. (1998) review potential candidates, Moser and Nicholas (2004) examine whether electricity was a GPT, & Jovanovic and Rousseau (2005) compare the impact of IT and electricity, to name just a few. However, it is considerably more difficult to investigate whether currently emerging technologies have the potential to become a GPT. The challenge arises because ex-ante even an exact definition of emerging technologies is difficult, without even talking about ways to measure their impact. Nevertheless, conquering this bumpy road is important, because GPT's inherent innovation processes - though promising huge effects for economic growth - are subject to market failures and hence innovations are assumed to arrive too late and to a too little extent in terms of social welfare (Bresnahan and Trajtenberg 1995). Hence, if nanotechnology can be identified as young, but emerging GPT, sustainable policy implications can be derived in order to resolve, at least partly, the occurring market failures that hamper positive effects on productivity, enduring growth and prosperity.

We thus aim to contribute to the question, if nanotechnology is to be called an emerging GPT by validating that it features the three characteristics argued for as typical for general purpose technologies: Pervasiveness of use (1) is ensured by the generality of purpose, stemming from the possibility to arrange nanoscaled structures encompassing new material properties for literally countless applications in nanomedicine, atomically precise manufacturing, fuel cell electrocatalysis, organic photovoltaic cells and so on. The scope for improvement (2) in nanotechnology is provided by the possible reduction of size and costs, and increasing complexity. For instance, nanoapplications in semiconductor manufacturing technology have resulted in a remarkable reduction of processing size in recent years (Graham and Iacopetta 2009). Hints for nanotechnology to spur innovation (3) in application sectors are given by the existence of a nano-oriented value chain with basic, intermediate and downstream innovations (Youtie et al. 2008). Wang and Guan (2012) distinguish four stages within this value chain: nanomaterials, nanointermediates, nano-enabled products and nanotools. The relationship between electronic microscopy and nanotechnology sketches such possible value chains with inherent feedback loops exemplarily: R&D advances in instruments [e.g. scanning tunneling microscopes (STMs) / atomic force microscopes (ATMs)] actually opened the opportunity to conduct systematical research on the nanoscale, while advances in nanotechnology applied in such microscopes improved their capacities remarkably (Palmberg and Nikulainen 2006, Youtie et al. 2008). Thus, quality adjusted prices for ATMs and STMs declined, due to the application of nanotechnology. Moreover, in combination with the significant drop in scale enhancing the advances in semiconductors, this can also be instanced as evidence for innovational complementarities [combination of (2) and (3)]. We hence propose that nanotechnology is a general purpose technology and are subsequently testing the following hypotheses:

Hypothesis 1 *Nanotechnology is increasingly becoming a widely-used, pervasive technology.*

Hypothesis 2 *Nanotechnology exhibits scope for ongoing technological improvement.*

Hypothesis 3 *Nanotechnology increasingly spurs innovation in application sectors.*

2 Methodology and Data

2.1 Previous Contributions and Systematic Extensions

In recent academic literature, nanotechnology has been progressively analyzed in order to identify economic trends attributable to its emerging nature. Various authors have contributed to the assembly of a holistic picture on nanotechnology's development, including Heinze (2004), who focuses on its worldwide expansion, Hullmann (2007), who examines data on markets, funding, companies, and patents and publications (concluding that nanotechnology easily has the potential to reach the level of the ICT's economic impact), Wong et al. (2007), who investigate the evolution of application areas, Meyer (2007), who emphasizes the integrating and field-connecting characteristics of instrumentation within nanotechnology, and Palmberg et al. (2009), who give a first broad overview on the development of nanotechnology. These lines of research already foreshadow nanotechnology being an emerging GPT. However, they neither formalize data analyses nor provide acknowledged measures for GPT traits, and thus lack a systematic investigation on this issue.

First systematized approaches to directly uncover GPTs (using patent data) were made by Hall and Trajtenberg (2006). They suggest measures for GPT attributes, such as a generality index, number of citations, and patent class growth, for patents themselves and for the patents that cite these patents. Alongside, basic approaches to investigate whether particularly nanotechnology might be a GPT were made by Palmberg and Nikulainen (2006).

However, they do not yet apply those indicators proposed by Hall and Trajtenberg (2006) to test their hypotheses. These were adopted first by Youtie et al. (2008), who tested indicators for generality and highlighted evidence for nano being as pervasive as GPTs like ICT. Moreover, they developed new indicators for innovation spawning. Graham and Iacopetta (2009) also tested for these two features, and Schultz and Joutz (2010) further deepened the topic, discovering a few very general emerging nano related fields with the potential for wide economic impact, and nano-fields that experience a more focused development path. Most recently, Shea et al. (2011) analyzed a sample of USPTO patenting activity of the first 25 nano-years, looking for early evidence that nanotechnology is a general purpose technology, assessing all three characteristics. Hence, first approaches to investigate GPT features within nanotechnology systematically have been developed. However, all of them were limited to patent applications and all investigating USPTO data.

We set out to not only further consolidate these existing approaches, particularly with respect to the indicators measuring the three GPT features, but we extend the analysis to publication data, in order to conquer both knowledge creation and application development. Moreover, although nano-activity has been subject to investigation by the OECD in recent years (Palmberg et al. 2009), to our knowledge there have not been any examinations of broadly accepted measures of GPT-characteristics within the EU27 yet. And finally, there has not been an answer to the need for distance measures between technology classes (Hall and Trajtenberg 2006): Though pervasiveness constitutes the most highlighted GPT trait, the commonly stressed indicator, namely the so called generality index, suffers from the lack of distinction between closely related and very dissimilar technological fields. We thus not only utilize well-established and consolidated indicators of GPT features such as generality, diffusion, and forward citation rates, but add contextualized technological coherence as a new weighted generality measure, which has been demanded by Hall and Trajtenberg (2006), and with which we aim to complete the set of instruments on hand. Within all our analyses, we compare nanotechnology's research output to the ones of ICT as accepted GPT and of the combustion engine (henceforth CE) as a non-GPT, representing an upper and lower benchmark respectively.

2.2 Development tracking of GPTs with Patents and Publications

Patents, despite all difficulties that arise in their use and interpretation [see Porter et al. (2008) for an overview as well as Hullmann and Meyer (2003) and Huang et al. (2010) for a more detailed discussion on bibliometric issues concerned with nanotechnology], are widely accepted as proxy for innovative activity (Griliches 1990). Especially citation structures facilitate tracing knowledge flows [see Fischer et al. (2009), Bresnahan (2010), Jaffe et al. (1993), OECD (2009), Thompson (2006)]. Hence for the following analysis, data of nano-patents with priority application year between 1980 and 2008 were extracted from the 'EPO Worldwide Patent Statistical Database' (PATSTAT), version September 2010, and divided in samples including worldwide data and solely today's EU27. To identify relevant nano-patents by their titles and abstracts, a validated (evolutionary) lexical search strategy was used, based upon an approach of merging keywords proposed by Mogoutov and Kahane (2007), Glänzel et al. (2003) and Porter et al. (2008). CE and ICT patents were identified using search terms previously used in the literature: For CE, the IPC (International Patent Classification) class 'F02' was sufficient (Graham and Iacopetta 2009), whereas for ICT the search term was based on class definitions the IPC itself proposes. The respective patent search queries can be found in the appendix.

In addition, the considered nano-related **publications** are indexed in the Thomson-ISI WoS database. Again we refer to the period between 1980 and 2008. As well as with patents, a Boolean search term was used in order to identify nano-related publications by searching for certain keywords (and excluding others) in the topic of every paper. The search term is likewise based on the aforementioned combination of different search queries, but, due to technical restrictions, way shorter than the patent search term. A respective lexical CE query was developed by ourselves. For our GPT-reference ICT, we extracted all publications that were allocated in the Thomson ISI Subject Areas (SA) 'Computer Science' and 'Telecommunications', since an arguable description via keywords seems to be impossible for this field (Schmoch 2011, personal communication). As with patents, publication queries can be found in the appendix.

3 Results and interpretation

3.1 Pervasiveness (H1)

For a technology to be(come) pervasive, it has to be widely applicable already at an early stage of its development thereby using different diffusion channels. Finding evidence for nanotechnology being a future GPT thus includes finding linkages to a broad variety of different industries and technologies. Examining diffusion rates as one possible indicator of pervasiveness, one might consider the share of nano-patents / publications to total patents / publications in the respective portfolios of the most innovative firms and institutes, as diffusion is assumed to be fastest in these. Therefore, we apply this first quantitative measure exemplarily to the TOP25 firms in the European R&D Investment Scoreboard 2010 for patents and to the TOP25 publishing institutions in Europe (following WoS) for publications. In Figure 1, we depict the shares of ICT-, CE-, and nano-patents of the Top25 firms over the past three decades. As the trend indicates, the fraction of ICT-patents in innovative companies shows only a slight increase over the past 20 years (where one should not overrate findings in the last few data points: Interpreting patent developments demands caution regarding the last years, since patent acceptance takes its time. Due to this lag the last year in our sample is 2008, even though the database ranges till September 2010). It thus seems that there is a quite constant output rate of new codified applications in information and communications technology, so the growth follows a linear pattern. This is not only true for these 25 chosen companies, but for our observations of all patents as well.

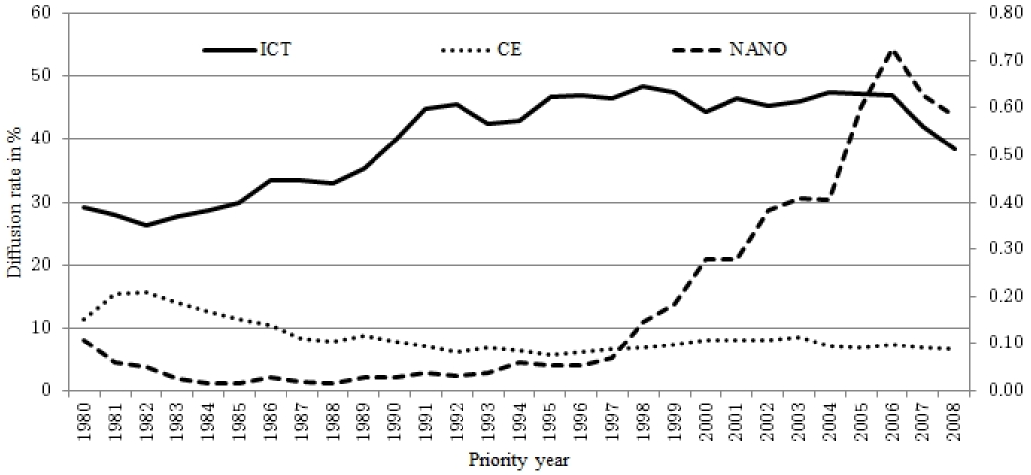

Figure 1: Patent Diffusion Rates of Top25 Firms in R&D, left axis: ICT and CE, right axis: nano

While the share of patents of our non-GPT proxy CE appears constant as well (around 7% for the last 20 years), the fraction of nano-patents seems to rise with a remarkable increase setting in about 1997. Nanotechnology inventions thus appear to gain in importance regarding their proportion of R&D-Output. But even in the observed companies with higher than average R&D intensity nanotechnology is still far away from outmatching the share of countable results in CE related research.

Scientific publications, though, are often associated with the more fundamental research, and nanotechnology evidences this quite clearly, as Figure 2 depicts. For the Top25 publishing institutions worldwide we observe shares of nano-related scientific literature around 6.5%, with an unbowed trend pointing to further growth in years to come. ICT shares of publications linger around 3%, with only a 1% increase in two decades. Hence ICT in general reveals a focus on applied research (as marked by patents), while nanotechnology is still primarily a matter of the scientific debate. Again, this is almost the same for the whole sample.

Already within their seminal paper, Bresnahan and Trajtenberg (1995) point to the possibility of identifying valuable inventions by patents that are cited by a wide range of

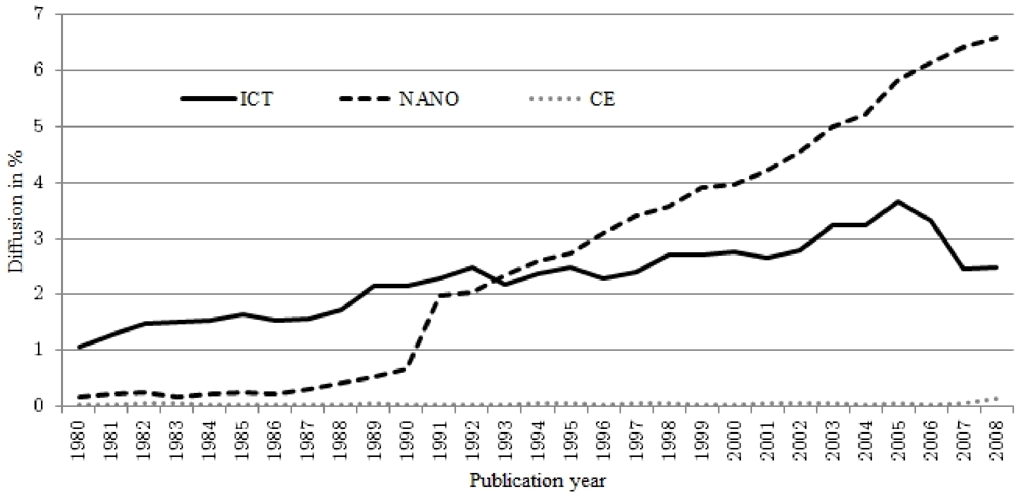

Figure 2: Diffusion Rates based upon publications of Top25 publishing institutions.

different industries. To measure this, Trajtenberg et al. (1997) employed the Hirschman-Herfindahl index, which was further developed by Moser and Nicholas (2004) and Hall and Trajtenberg (2006) as generality index $G_i = 1 - \sum_j^{n_i} s_{ij}^2$, where s_{ij} denotes the percentage of citations received by patent i assigned to patent class j, out of n_i technological classes. If a patent benefited subsequent inventions in a wide range of technological fields, its generality index will be close to one, whereas if most of its forward citations are concentrated in a small number of fields G_i will be close to zero. Correcting for the citation lag bias (small forward time windows associated with young and emerging technologies pose difficulties in calculating sensible generality indices, since not all the citations are yet observed, thus s_{ij} is biased downwards) is possible by using $\tilde{G}_i = \frac{N_i}{N_i - 1} G_i$, where N_i denotes the total number of observed citations (Hall 2002). With respect to patents the generality index can not only be applied to IPC classes, but also be computed across technological fields in concordance with the International Standard Industrial Classification (ISIC) system. Such an aggregation generates less and broader defined classes, sharpening their distinctness, and yielding more meaningful generality indices. Thus, in our analysis, the underlying classes n_i do not represent 4-digit patent IPC classes, but 30 technological fields, in which these IPC classes are categorized in [following the NACE/ISIC Concordance developed by Hinze et al. (1997) according to OST/INPI/ISI - Observatoire des Sciences et Techniques / Institut Nationale de la Proprieté Industrielle / Fraunhofer Institut für System- und Innovationsforschung]. Calculations based upon IPC classes and their aggregation to 44 technological areas as developed by Schmoch et al. (2003) are available upon request. Figure 3 shows yearly average forward generality Indices of the Top10 cited patents according to the K30 technology classification (World data, EU27 available as well). Note that for CE we have calculated values for 5-year-intervals only, as we intended to keep the utilized amount of data at a reasonable level. Intermediate values are linearly interpolated. However, there is no reason to expect robustness problems by extending the data set.

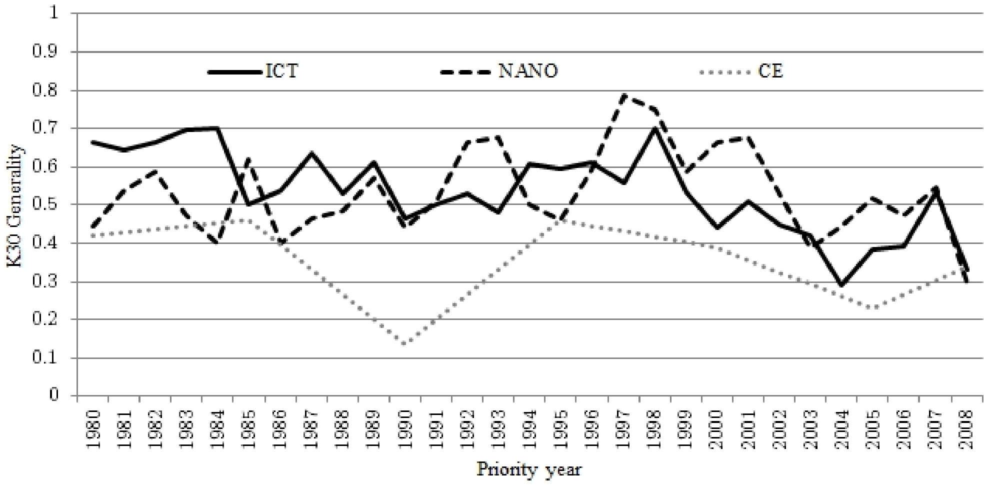

Figure 3: Forward Average Generalities of Top10 Cited Patents p.a. (K30)

Comparatively low generality indices seen in Figure 3 are explainable considering the fact that a smaller number of classes is taken into account: Less distinguishable classes entail smaller generality values, since all percentages of citations received by a patent are divided in fewer categories before their squares are summed up. The higher this sum becomes, the lower is the index. Fewer classes thus provide a higher accuracy of discrimination between pervasive technologies and those, of which the citation structure refers to a more limited number of fields. This is clearly to be seen in the figure: The average generality values of our lower benchmark CE are almost everywhere considerably smaller than those of ICT and nanotechnology. This holds true for the European sample.

The generality index is not restricted to patents. Publication data and the corresponding classification system of Subject Areas (SA) in Thomson ISI WoS can be used similarly. However, we do not show the results of our publication generalities here, since they offer little additional information: Classification within subject areas is subject to minor objectivity, which results in hardly distinguishable average generality indices.

The problem with generalities is best expressed by Hall and Trajtenberg (2006):

’[...] all of the generality measures suffer from the fact that they treat technologies that are closely related but not in the same class in the same way that they treat very distant technologies. This inevitably means that generality may be overestimated in some cases and underestimated in others. One suggestion for future research would be to construct a weighted

generality measure, where the weights are inversely related to the overall probability that one class cites another class.'

We use a measure of technological coherence (TC) to approach this goal, which in our context will be defined as the extent to which inventions, i.e. patents, in a technological area share the same underlying knowledge. TC reflects the average relatedness of those classes, a patent is associated with, either because of being sorted in those classes or cited by them. Hence, to calculate the coherence of a patent portfolio, the degree of relatedness has to be determined for each pair of technology classes. Commonly, as e.g. in Breschi et al. (2003) and Leten et al. (2007), this is done using co-occurences of technological classes that are jointly associated to a patent. We will not recalculate the required relatedness matrix (with elements R_{ij}), but use the one constructed by Leten et al. (2007), which uses the OST / INPI / ISI concordance with 30 distinct tech fields. Following their citational approach, two technology classes are considered as technologically related if patents associated to one technology class often (i.e. more often than could be expected assuming random citation patterns) cite patents classified in the other technology class and vice versa. The patent-count weighted average relatedness $COH_i = \frac{\sum_{i \neq j} R_{ij} \times P_j}{\sum_{i \neq j} P_j}$, of technology i to all other technologies relevant in the considered year then leads to an overall coherence measure of (for example nanotechnology) patents as a weighted average of all the COH_i measures: $COH = \frac{\sum_i P_i \times COH_i}{\sum_i P_i}$. We thus calculate the TC of (i) nano-patents applied for, and (ii) nano-patents citing patents, both within one year. TC can reasonably assumed to be higher, the more specialized a technological field is. New inventions in specialized fields are expected to be somewhat more *coherent* than are inventions in the field of a general purpose technology. By definition, GPT related inventions can be found in a wide range of application fields, and thus their TC is expected to be considerably smaller. We will employ this measure for the first time in this connection.

Figure 4 shows the results for our TC-measure (i) based on world data. The GPT proxy ICT and nanotechnology shape a narrow side-by-side course with visible distance to the CE coherence values. To verify the significance of this offset we perform a two sample location t-test (which can be found in the appendix). The results are robust when taking the technology classes of citing patents (ii) instead of the cited patents technology classes themselves, as well as when restricting the data to European patents (both available upon request). The measure is restricted to patents, since it relies on the relatedness matrix by Leten et al. (2007). Nonetheless, a similar matrix for publications might be constructed in further research.

With this new measure it becomes clear, that pervasiveness is undoubtedly much stronger for our ICT and the GPT candidate nanotechnology. Both show a visible distance to the lower benchmark technology CE, ICT with a smoother line due to the clearer basis in the categorization system, nanotechnology with soft swings and a slight increase in coherence

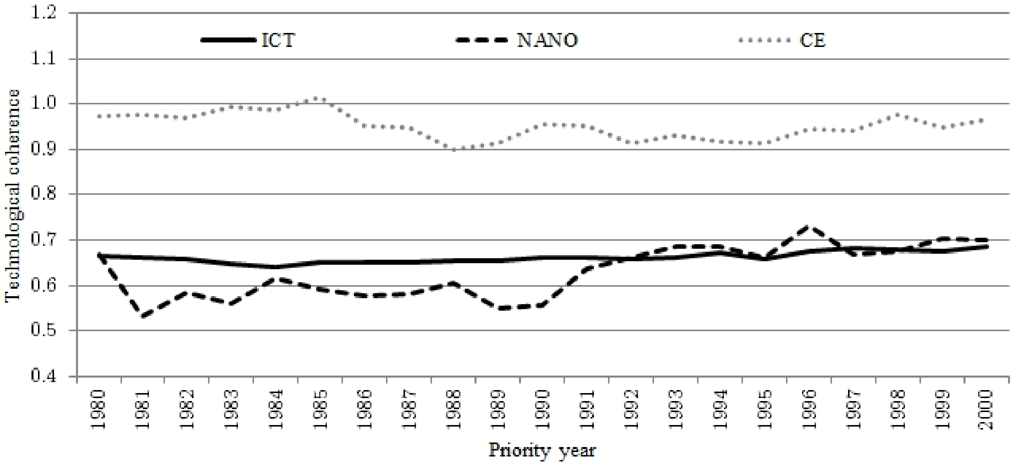

Figure 4: Technological Coherence of ICT-, Nano- and CE-Patents (World data).

after 1990, the starting point of a significant rise in the number of nanotechnology patents, possibly due to a related small gain in concentration among technology classes.

3.2 Scope for Improvement (H2)

GPTs are improved continuously at every level of the value creation chain. Regarding nanotechnology and its potential to further reduce cost, size and enhance or even redefine material characteristics regarding stability, flexibility, abrasiveness, electrical properties and so on, two simple indicators shall illustrate the hitherto manifested scope for improvement.

With the first one we follow the suggestion of Palmberg and Nikulainen (2006) by observing the pure number of patents. We do not depict the results here for the sake of brevity, but as expectable, the number of nanotechnology patents has evolved noticeably over the past decades, though it is still far from reaching that of CE (not to mention ICT), a result strongly related to the contemporaneous lack of countable applications for the emerging technical feasibilities. As well as for diffusion rates, publications on the other hand again underscore the fundamental theoretical work that has been done for nanotechnology in the past 20 years. With the pure number of publications surpassing those of ICT at around the year 2000, nanotechnology has become *the* object of scientific interest of the new century. Nanotechnology's scope for ongoing improvements is thus unbowed, and there is little reason to expect any attenuation within the next years.

Our second indicator is based upon Schultz and Joutz (2010), who propose a later patent citing the original invention as an indicator for continual technological improvements. Following Hypothesis 2, nano-patents are hence expected to have many citations indicating a pattern of cumulative innovation (Hall and Trajtenberg 2006), an expectation which can easily be transferred to publications. In fact, we find nanotechnology producing patent citation rates even above those of ICT (and all patents worldwide, see Figure 5). A small absolute number of nano core patents produces comparably large numbers of references. These core technology founding patents seem to stem from outside Europe, since those nanotechnology patents we find in the European union have considerably smaller citation rates.

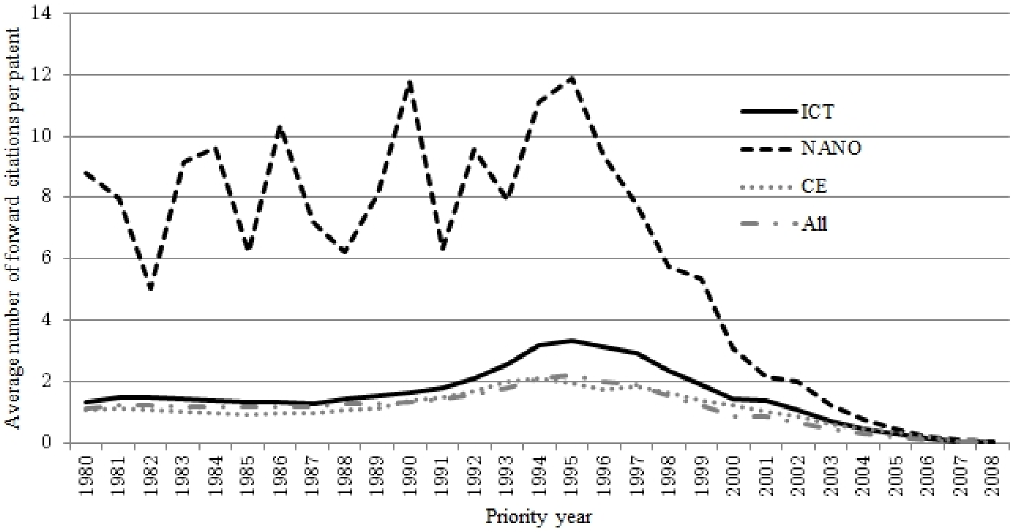

Figure 5: Forward Citation Rates ICT-, Nano- and CE-Patents (World data).

Publications are not affected that much by borderlines, and thus European publications again show high nano-related citation rates (due to database restrictions using scientific publications from WoS is considerably more difficult, which is why we limit ourselves to the European Union regarding publications). Again, visualized results are available upon request.

3.3 Innovation spawning (H3)

In the field of nanotechnology, innovation spawning can be found in the existence of nanoenhanced value creation chains, consisting of initial, intermediate, and downstream innovations. nanoscale structures (carbon nanotubes, quantum dots, fullerenes and so on) embodied in products with nanoscale features (coatings, optical components, or memory chips) and finally employed in a variety of final products (such as airplanes, computers, clothing, or pharmaceuticals) can be identified as such (Lux Research (2006), Youtie et al.

(2008)). In combination with technological dynamism, this characteristic is the main driver of innovational complementarities.

An increasing share of nano-inventions in overall patenting activity can be used as an indicator for the innovation spawning characteristic of nanotechnology. As for our Top25 firm sample, for the most part we find similar trends for the fraction of nano-, ICT-, and CE-patents worldwide, which is why we do not visualize them here. On account of this and for the sake of brevity again, we will focus instead on another indicator, namely the growth in nano-citing technological classes. If hypothesis 3 can be supported, nano-patents-citing tech classes are subject to a burst of innovations because they grow with the number of complementary goods developed (Hall and Trajtenberg 2006). A proxy for innovation spawning can hence also be the growth of technology classes (or subject areas with respect to publications) that harbour (nano-) citing patents / publications, as proposed by Hall and Trajtenberg (2006). Therefore we chose ten top citing patent classes (available upon request) according to their number of references, and ten subject areas according to a score system that accounts for the Top25 cited publications and the occurrence of their citations in these different subject areas. In the resulting diagram (figure 6) we cut the time before 1988, since we observed just a few classes in the beginning of nanotechnology's evolution, of which excessive average growth would lead to the false impression that nanotechnology's trend was decreasing.

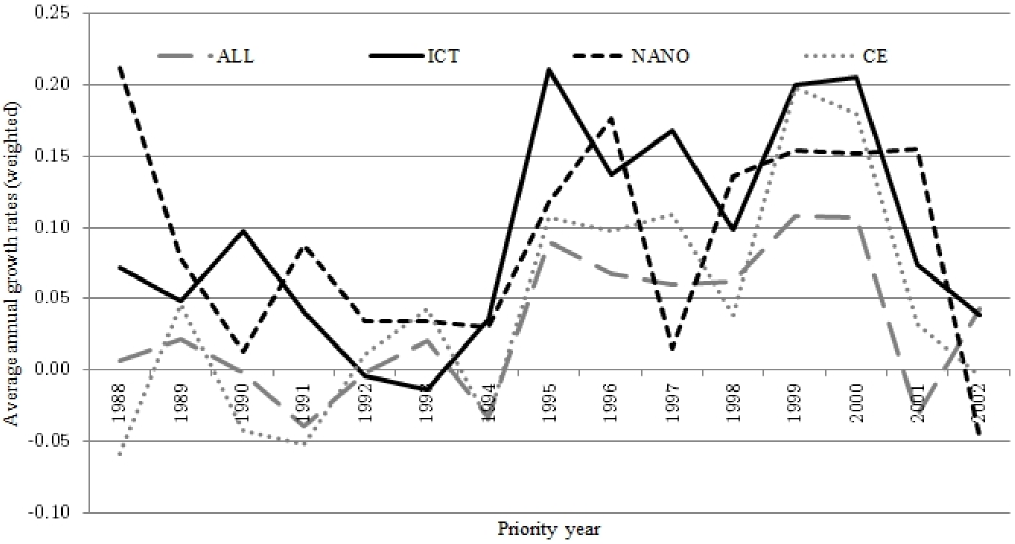

Figure 6: Growth of Top Citing Classes, ICT-, Nano- and CE-Patents (World data).

We cut above 2002 as well, since with declining overall citation rates (remember Figure 5) the average class growth becomes much less conclusive. Especially in highly complex technological areas (including undisputably our three compared technologies ICT, nanotechnology and CE) citations and therefore continual advancements take their time. So while we are not willing to conceal an observed below-average class growth for all of those three technologies after 2002, one has to point out that the choice of classes is biased due to the declining observable citations. Thus with time, other classes might become more meaningful as predictor for an above-average class growth. Reselection of classes every year would lead to incomparability though, which is why being careful in interpreting the years after around 2000 is mostly without alternative.

For the remaining observation period nanotechnology and ICT both prove to be outstanding in their innovation spawning character. Almost without exception (1997 Nano, 1993 ICT) we find citing class growth to be above average. Admittedly, the lower benchmark CE does not perform too badly for this indicator as well, which is not surprising however: Though CE is not considered as GPT here, its ability to spawn innovation - even above average - within a less pervasive set of technological classes is unquestionable. Finally, regarding publications as supporting indicator, we do not observe significant above average growth rates. A straightforward explanation is yet to be found, but one might guess that the method we chose to select the top ten subject areas (with the above-mentioned score system) could be responsible for that outcome.

Table 1 provides an overview of all our hypotheses, the analyzed measures and the corresponding results. Statements within the *Support* column reflect significant results from our t-tests regarding the visualized offsets (see results for generality and coherence in the appendix) as well as our qualitative assessment with respect to level and trend. Keep in mind that the overall evaluation of the three GPT traits pervasiveness, scope for improvement, and innovation spawning ultimately relies on comparisons to the chosen benchmark technologies. Without these acknowledged counterparts and their scale function, any presented measure would lack relativization.

4 Conclusion

Stating that nanotechnology is widely considered as *the* general purpose technology of coming decades yields huge promises regarding consequent impacts on long term economic growth. GPT's three constituting characteristics pervasiveness, high technological dynamism and innovation spawning in various application fields have therefore been object of many studies. We contributed to this research by extending the underlying data to scientific publications, regarding Europe as examined region for the very first time, and adding up a new measure with technological coherence as demanded for. With an upper and lower benchmark technology, information and communication technology and the

Hypothesis	Indicator	Result of Nanotechnology	Support
H1 Pervasiveness	Diffusion TOP25	PAT: way below ICT & CE, pos. trend	weak
		PUB: above ICT and CE	strong
	Generality	Nano roughly between ICT and CE	strong
	Technological Coherence	Nano and ICT way below CE	strong
H2 Scope for Improvement	Increase of Nano-Inventions	PAT: way below ICT & CE, pos. trend	medium
		PUB: way above CE, surpassing ICT	strong
	Forward Citation	PAT: way above ICT and CE/ALL (W)	strong
		PUB: way above ICT and CE/ALL (EU27)	strong
H3 Innovation Spawning	Diffusion	PAT: way below ICT, trends tw. CE (W)	medium
		PUB: way above CE, surpassing ICT (EU27)	strong
	Citing Class Growth	PAT: above average, similar to ICT	strong
		PUB: average, below ICT, similar to CE	weak

Table 1: Overview of Results Supporting the Hypotheses

combustion engine, respectively, we provided comprehensive counterparts which proved to be useful comparisons.

The results indicate that nanotechnology evolves as GPT, as predicted by both scholars and practitioners. While it remains unclear if it yields similar potential as ICT has shown in the past two decades, nanotechnology's development regarding its unbowed continual advancement is undisputably as promising, as far as the data tell. Certainly, the incorporation of R&D expenditures representing the input side would enable important insights when combining these two perspectives, offering explanations of macroeconomic growth already on the micro-level by investigating incentives and their interdependencies. This enrichment should facilitate the political discussion regarding emerging GPTs, especially as soon as country-level data reveals catch-up potentials. Moreover, by adding impact measures of national (or for instance European) and institutional technological leverage capabilities, inference statistics could provide a more holistic view on nanotechnology and even more, on GPTs altogether.

5 Appendix

5.1 Patent Identification - Search Terms and IPC Classes

Nano Patent Search Term

The query that identified nano-patents was generated searching for the following terms in title and abstract (refering to Mogoutov and Kahane (2007), Glänzel et al. (2003) and Porter et al. (2008)):

> nano; carbon tube; mechanical resonator; quantum dot; low dimensional system; semiconductor structure; li batter; solar cell; carbon composite; carbon fiber; field emitter; crystal memory; emission propert; thin film; carbon film; film deposit; gold catalyst; tube modified; gold particle; plga particle; heterogeneous catalyst; composite powder; tribological propert; composite coating; composite coating; silicate, composite; clay composite; polymer composite; composite prepared; coating deposited; lipid particle; al2o3 composite; coating produced; sol method; semiconducting material; diamond film; mesoporous material; soft magnetic material; primordial protein; block copolymer; hydrogen storage material; zinc compound; clay composite; walled carbon; metallic carbon; semiconducting carbon; single carbon; surface plasmon; finite-difference time-domain method; chemisorption; atomistic simulation; tio2 solar; sensitized tio2; dye solar; sensitized solar; electrochemical performance; induced deposition; field emission; vapor deposition; crystalline diamond; chemical vapor; ion implantation; plasma chemical; magnetic fluid; crystalline silicon; crystal morphology; laser ablation; laser deposition; beam epitaxy; sputtering; molecular beam epitaxy; mesoporous silica; solid lipid; drug carrier; enhanced raman; co oxidation; direct electrochemistry; electrode modified; raman scattering; immunosensor based; resonance light; modified glassy; glucose biosensor; biosensor based; electrochemical biosensor; drug delivery; modified electrode; amorphous alloy; delivery system; surface chemistry; ball milling; drug release; heterogeneous catalysis; spark plasma; supramolecular chemistry; gene delivery; severe plastic; gel method; mechanical alloy; plasma sintering; gold electrode; situ polymerization; carbon electrode; single-molecule; biosensor; oligomeric silsesquioxane; metallic glass; poly methacrylate; block copolymer; grain growth; plastic deformation; sintering; microstructural evolution; microstructure superplasticity; surface plasmons; electrostatic force microscopy; transmission electron microscopy; quantum rings; chemical vapor deposition; graphitic carbon; dye-sensitized solar cell; magnetization reversal; porous carbon; supercapacitor; growth from solutions; diamond-like carbon; mesoporous; self-assembly; surface-enhanced raman; mechanical alloying; spark plasma sintering; ball milling; montmorillonite; organoclay; electrospinning; amorphous alloy,

and excluding the following words:

> nano2; nano3; nano4; nano5; nano liter; nano second,

always in-/excluding different orthographic versions and words with differing suffixes.

ICT Patent Search Term

We searched for the following IPC classes, refering to the 8th edition of IPC:

> Telecommunications:
> G01S; G08C; G09C; H01P; H01Q; H01S; H1S5; H03B; H03C; H03D; H03H; H03M; H04B; H04J; H04K; H04L; H04M; H04Q;
> Consumer Electronics:
> G11B; H03F; H03G; H03J; H04H; H04N; H04R; H04S;
> Computers, Office Machinery:
> B07C; B41J; B41K; G02F; G03G; G05F; G06; G07; G09G; G10L; G11C; H03K; H03L;
> Other ICT:
> G01B; G01C; G01D; G01F; G01G; G01H; G01J; G01K; G01L; G01M; G01N; G01P; G01R; G01V; G01W; G02B6; G05B; G08G; G09B; H01B11; H01J; H01L

CE Patent Search Term

IPC class 'F02' sufficient (Graham and Iacopetta 2009).

5.2 Publication Identification - Search Terms and Subject Areas

Nano Publication Search Term

Based on a combination of different search queries, again relying on Mogoutov and Kahane (2007), Glänzel et al. (2003) and Porter et al. (2008) but, due to WoS database restrictions, shorter than the patent equivalent:

> (SO=(nano*) OR TS=(nano* NOT(nano2, nano3, nano4, Nano5, nanosecon*, nanoliter*)) OR TS=("quantum dot*" OR "quantum wire*" OR "beam epitaxy*" OR "molecul* engineer*" OR "carbon tub*" OR "fulleren*" OR "self assembl* monolayer*" OR "self assembl* dot*" OR "molecul* self assembl*" OR "single carbon*" OR "single molecule*" OR "atom* force microscop*" OR "tunnel* microscop*" OR "drug delivery" OR "walled carbon" OR "composite* coating" OR "thin film" OR "microstructure*" OR "semiconducting material*" OR "singe electron*" OR "atomic(w)layer" OR "molecular manipulation" OR "quantum wire?" OR "quantum devic*" OR "molecul* manufactur*" OR "molecular motor" OR "drug carrier" OR "single electron* tunneling" OR "supramolecular chemistry" OR "molecular templates" OR "soft lithograph*" OR "tube* modified" OR "vapor deposition" OR "ball milling"))

ICT Publication Search Term

Sufficient Thomson ISI subject areas (according to Schmoch 2011, personal communication):

> ’Computer Science’ and ’Telecommunications’

CE Publication Search Term

Self-developed:

> (SO=("combustion engine*") OR TS=("combustion engine*" OR "CI engine*" OR "compression ignition engine*" OR "combustion motor" OR "combustion product" OR "combustion-product" OR "otto engine*" OR "otto cycle*" OR "diesel engine*" OR "diesel cycle*" OR "two-stroke engine*" OR "two stroke engine*" OR "four-stroke engine*" OR "four stroke engine*" OR "six-stroke engine*" OR "six stroke engine*" OR "wankel engine*" OR "wankel rotary engine*"))

5.3 Additional Tables

GEN	Obs	Mean	StdDev	ICT	CE	EU27
			WORLD			
NANO IPC4	29	0.6641966	0.1032072	0.3501	-1.0292	0.1826
ICT IPC4	29	0.6536655	0.1248327		-1.073	-0.5169
CE IPC4	29	0.7052571	0.0339752			4.4614***
NANO K30	29	0.5338897	0.1143927	-0.0403	3.7965***	-0.9671
ICT K30	29	0.5350828	0.1109072		3.9159***	-0.3279
CE K30	29	0.3481571	0.1241372			-0.1561
			EU27			
NANO IPC4	29	0.6638345	0.1066706	-0.1067	3.5665***	
ICT IPC4	29	0.6665345	0.0848104		4.2438***	
CE IPC4	29	0.5779069	0.0738608			
NANO K30	29	0.5353483	0.1144757	-0.2821	6.7428***	
ICT K30	29	0.5425276	0.0753934		8.7179***	
CE K30	29	0.3539414	0.0888042			

Table 2: t-Tests (unpaired) of Fw. avg. Generalities (IPC4, K30) for Nano, ICT and CE patents, World, EU27 across years. Right column: Paired t-tests between WORLD and EU group values. ***Indicates significance at 0.01.

COH	Obs	Mean	StdDev	ICT	CE	EU27
		WORLD				
NANO	21	0.6304762	0.0594539	-2.4374**	-22.0292***	0.8630
ICT	21	0.6628571	0.0130931		-39.9758***	0.4385
CE	21	0.9514286	0.0303786			-1.0831
NANO fw	21	0.662381	0.0811113	-0.1871	-7.9591***	-0.9516
ICT fw	21	0.6490476	0.0434632		-14.9552***	7.5255***
CE fw	21	0.9066667	0.0512185			-10.4017***
		EU27				
NANO	21	0.62	0.0870057	-2.1688**	-16.8209***	
ICT	21	0.6614286	0.0096363		-39.7650***	
CE	21	0.9619048	0.0332594			
NANO fw	21	0.6447619	0.0955311	1.9996*	-11.6696***	
ICT fw	21	0.6238095	0.0351392		-20.8685***	
CE fw	21	0.817619	0.0279114			

Table 3: t-Tests (unpaired) of Coherences of Nano, ICT and CE Patents and Forward Citing Patents (fw) across Time. Right column: Paired t-tests between WORLD and EU group values. ***Indicates significance at .01.

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