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**Abstract**

There is a growing need for fresh and systematic evidence about company innovation in emerging technologies such as nanotechnology. It is particularly important to track shifts from discovery to commercialization at the later stages of the innovation process, where diverse product and financial strategies may be pursued. This paper presents results from a pilot study of of small and medium-sized enterprises (SMEs) based on a web-scraping and content analysis of current and archived nanotechnology enterprise web sites. We use this novel approach to explore nanotechnology SMEs transitions from discovery to commercialization and understand how transitions vary by SME characteristics, technology and market sectors. A sample of 30 US nanotechnology SME web sites is analyzed, covering a time period that ranges from 1997 to 2010. Our findings suggest that although the idealized linear innovation model is present, important instances of divergence exist.  In particular, federal funding and conferences, both expected to characterize early research stages also play a role in late stage commercialization. Factor analysis uncovered sectoral differences between nanobiotechnology, nanoelectronics and nanoenergy. While this pilot analysis has limitations of sample size, it demonstrate the potential of using web-scraping techniques to offer new insights about enterprise commercialization strategies.Keywords:

**Small and medium enterprise; emerging technology; nanotechnology; commercialization; strategy; innovation; Web sources**

## 1. Introduction

The realization of economic and social value from emerging technologies typically encompasses a long time-frame, with many uncertainties involved in the processes of transition from scientific discovery to application and commercialization. This is especially the case in emerging science-driven technologies, such as nanotechnology, where significant public and private investments have been made in R&D in anticipation of securing explicit economic and societal results. It is both important and challenging for stakeholders concerned with innovation and commercialization (including entrepreneurs, research managers, science and technology policymakers, and regulators) to be able to monitor and understand what business strategies and models are likely to lead to successful outcomes. Advanced science and new inventions are often assumed to automatically translate into successful commercialization and societal benefit. It is rarely so straightforward. Ongoing attention is required not only to improving appreciation of the range of innovation models that companies in emerging industries adopt and evolve, but also to enhancing the range of information sources that can be drawn upon to provide an evidence base for enterprise strategy assessment and analysis of innovation in emerging technologies.

While there are a series of well-tried sources of information on enterprise innovation, including patents and surveys, such sources have limitations in terms of coverage, timeliness, and response. New strategies are required to study evolving enterprise models. In this paper, we adapt an approach ("web-scraping") – which has been implemented in other fields including computer science – to collect current and archival web-based information about the innovation models used by a set of small and medium-sized enterprises (SMEs) in the United States in the emerging domain of nanotechnology. We first consider the rise of nanotechnology development and the role of SMEs in this field. We then review literature and debate about the business strategies and commercialization models of SMEs in emerging technologies, and present propositions about the approaches that we anticipate being pursued by SMEs in nanotechnology. This is followed by a discussion of the web-based techniques used to provide information and evidence for a pilot sample of 30 SMEs associated with the US National Nanotechnology Infrastructure Network (NNIN). We present the results of our analysis of this data, examining for these SMEs how their innovation approaches, technologies, product introduction methods, relationships and funding sources develop over time. The analysis considers the influence of industry characteristics within the sample by segments including nanoelectronics, bionanotechnology, and nanoenergy. We conclude with a discussion of conclusions as well as an appraisal of the potential and limitations of our method and analysis.

## 2. Nanotechnology Development

Nanotechnology is an emerging domain of new knowledge production and commercial interest that involves the understanding and manipulation of molecular-sized materials (with dimensions under 100 nanometers) to create new products and processes with novel features due to nanoscale properties. Over the past decade, there has been a burgeoning of global research, business and policy interest among developed and many developing countries in nanotechnology, with significant commitments of public and private funding (Anon and Wang

2010). The United States is the world's largest sponsor of nanotechnology research and development. US federal government investment in nanotechnology R&D is budgeted at more than $1.7 billion for fiscal year 2011. Since 2001, the cumulative total of dedicated federal government investment in nanotechnology is $12 billion (PCAST 2010). Additionally, US business nanotechnology R&D funding has been estimated at around $2 billion annually. While the federal government sponsors basic nanoscience research, most corporate funding is for applied development, focusing in electronics, manufacturing and materials, and healthcare and life sciences (Lux 2007).

Although public and private R&D investment in nanotechnology is large, applications are still in their early stages (Roco 2005). Nonetheless, nanotechnology is expected to become a key driver of new technology-oriented business and economic growth (Lux 2007, NSET 2007). In this respect, nanotechnology is akin to other novel science-driven technologies which also deliver new capabilities and performance enhancement. Nanotechnology – as a platform technology with applicability across multiple sectors of the economy including consumer goods, health diagnosis and medical care, energy, environment, electronics, construction, and defense – may also have the characteristics of a general purpose technology with potentially broad implications in redefining products, industries, skills, and places (Anon et al. 2008, Graham and Iacopetta 2011). Yet, to realize its promised economic benefits, nanotechnology must transition from discovery to innovation. There is some recognition that, to date, the commercial applications of nanotechnology have failed to meet the high expectations advanced in the early growth years of the field. In part, private-sector nanotechnology growth has been dampened by global financial crisis and economic slowdown which began in 2008. Additionally, the complexities of nanotechnology, including challenges of scalability, access to funding, human resources availability, regulation and risk perception, have been identified as barriers, especially for SMEs (OECD, 2010). Yet, it is evident that there is an underlying trajectory of nanotechnology development towards commercialization. Based on the ratio of patent applications to research, Anon et al. (2011) find that in the 2000-to-2003 timeframe, a shift from research to commercialization is evidenced. Currently, many commercial applications of nanotechnology are incremental improvements to existing products, but as we move towards the 2020s, more fundamental innovations are anticipated (Roco et al, 2011). The National Nanotechnology Initiative (NNI), which was announced in 2000, is the coordinating mechanism in the US for federal agencies involved in nanotechnology R&D, regulation, and policy. The NNI is guided by the legislative framework set out in the 21st Century Nanotechnology Research and Development Act of 2003, one goal of which is "accelerating the deployment and application of nanotechnology research and development in the private sector, including startup companies." (21st Century Nanotechnology Research & Development Act 2003) Among other measures to stimulate business outcomes from the massive US investment in nanotechnology R&D, the NNI established a program of Nanotechnology Signature Initiatives for FY 2011 to increase the pace of nanotechnology innovations in "areas ripe for significant advances" (NNI 2011). There is also ongoing investment in the availability of user facilities, including through the NNIN, to support companies to undertake applied research and form partnerships with universities so as to advance nanotechnology applications. (NNIN 2011)

Thus, there is recognition that in order for nanotechnology discoveries to realize their potential for economic impact and to generate enterprise, employment and wealth, private sector innovation must follow and be interrelated with research. Yet, at present, our understanding of the highly complex and dynamic processes of innovation in emerging technologies such as nanotechnology is fragmented: too often, studies have been hampered not only by lack of data (Schramm 2008) but also by adopting a static view of survivors in what is a failure-prone multi-year process or by focusing analysis primarily on the research phase and on public sector actors.

In this study, our focus is not just on new research discoveries and inventions but on innovations or new applications. This distinction is important. Research discoveries can be tracked by bibliometric analysis of publications, while technological inventions can be proxied (at least to a reasonable degree) by tracking of patents (Jaffe and Trajtenberg 2002). However, the measurement of innovations and new applications requires a more complex analytical approach which goes beyond the examination of patents (OECD 2005). The assessment and analysis of innovation requires identifying new or improved product or process introductions and ascertaining targeted markets. New organizational relationships (including linkages between enterprises and universities or innovation partnerships among enterprises) may be associated with new technological innovations (von Hippel 1998, Chesbrough 2003). SMEs, including established innovative small firms as well as new start-up enterprises, have been found to be significant actors in the invention and innovation process (Acs and Audretsch 1990, Anon and Hegde 2005, Anon 2010). (SMEs are generally defined as enterprises with 500 or fewer employees (SBA 2011)). In technology-oriented sectors, SMEs appear to be disproportionally active in pioneering a series of important innovations (Baumol 2005), including in life-science domains such as biotechnology, pharmaceuticals, and medical devices (Breitzman and Anon 2008). As might be expected, in nanotechnology, SMEs are active players. However, as a cross-cutting platform technology, nanotechnology engages not only many industries but also large incumbent firms engaged in volume production. Indeed Rothaermel and Thursby (2007) argue that a distinctive attribute of nanotechnology is the early involvement of large incumbent firms, which differs from the biotechnology paradigm of innovation emerging from small startups often with a university relationship. Nonetheless, there are clearly roles for both small and large enterprises, with a high-level of venture start-up and spin-off activity seen across the nanotechnology field.

As the nanotechnology field evolves, we would expect the innovation strategies of SMEs to similarly change and develop. In the next section, we review literature which discusses the factors and issues that influence SME innovation in emerging technologies and use this as a backcloth to consider how nanotechnology SMEs might develop their own strategies.

## 3. Innovative SMEs and nanotechnology development

Wang (2007) identified several hundred new nanotechnology-based venture start-ups formed in the US by 2005, half of which were university spinoffs. Fernandez-Ribas reports that small and medium-sized enterprises (SMEs) account for one-third of all US companies with World Intellectual Property Organization (WIPO) Patent Cooperation Treaty (PCT) filings in nanotechnology domains. Relative to large corporations, the role of SMEs in WIPO nanotechnology patenting has grown over the past 10 years (Fernandez-Ribas 2010).

These observations about the emergence of nanotechnology SMEs suggest that they are playing an important part in the transition of nanotechnology from the laboratory toward innovation. It has been observed that high-technology SMEs are often associated with discontinuous or radical innovations (Dodgson and Rothwell 1994). We anticipate that the role of SMEs may be particularly critical in pioneering innovations as the nanotechnology field accelerates its shift from passive nanotechnologies (which often lead to incremental improvements in existing products) towards next generation active nanostructures (with more radical innovations). Research publications focused on active nanostructures experienced a two-and-a-half times increase in annual worldwide production from 2005 to 2008, with the US producing about one-third of these publications (Subramanian 2010). This expansion may be a leading indicator of an emerging wave of scientific discoveries in active nanostructures within universities that may generate entrepreneurial spinoffs.

In the industrial era, an SME could package its technology and intellectual property into a product, then manufacture and market it. Large established industrial firms were important in scaling up entrepreneurial ideas (Baumol 2004) in part because of their ownership of complementary assets relative to inventors (Teece 1986). This process was not unproblematic, however. High-tech startups naturally dedicate themselves to developing and engineering their new technology, and have always found the marketing side to be testing. If identifying customer needs and finding markets was difficult in the past, it is even more complex and critical today. The balance between suppliers and customers has changed and far more attention to meeting customer needs is required (Teece 2010). Additionally, ownership of complementary assets is less dominating because of the availability of contracting for manufacturing, marketing or other complementary capabilities (Grossman and Rossi-Hansberg 2008). Moreover, in an emerging technology such as nanotechnology, consumer acceptance is uncertain, potential risks may appear, and governmental engagement is high. This means that innovative companies frequently have to engage and collaborate with a wide sphere of business and public stakeholders as they seek to guide and apply their inventive efforts (Smits et al, 2010). Those who encourage innovation to meet societal need must understand how discovery-driven companies cope with these new challenges in the emerging business environment.

Today the innovator faces many more choices as well as the necessity of visibly creating value for users. To capture the nature of this more complex task, Teece and Chesbrough propose attention to business models (Teece 2010, Chesbrough and Rosenbloom 2002). They argue that the models are arrived at through an iterative design process and are highly context dependent. Additionally, Teece observes that nowadays effective innovation requires careful alignment with bundled complementary products and services but too many small firms still offer discrete devices or components believed superior simply because they incorporate a new technology.

Recent work on disaggregating the strategies of technology-intensive SMEs (Baumol 2005, Libaers et al, 2010) has uncovered diversity in the models innovative SMEs use to commercialize their technology, while at the same time pointing out that biosciences firms tend to be more homogenous in their adoption of a "technology pipeline" approach to commercialization through developing and licensing inventions. The dominance of the one model in the most visible discovery-based sector perhaps obscures from scholars the possibility that in other areas small innovative discovery-based firms face challenges in identifying the best route to commercialize their technology. In information technology for example, firms must identify the ideal blend of product and service provision. Other areas adopt custom engineering models. These results point to the need to investigate the issue in more depth.

We propose that nanotechnology SMEs must through trial and error devise innovation models to deliver value to customers and align their technology with existing solutions if discoveries are to be widely used in society and deliver on their promised benefits. The challenges they face differ from those of the previous generation of high-tech startups in biotechnology, and the solutions they find may offer guidance to future generations of technology-based SMEs. In particular, we seek to explore and test the following two propositions:

**Proposition 1. The introduction of nanotechnology innovations will follow diverse paths rather than singular or binary paths, influenced by technological sector characteristics and enterprise positioning**. Across all sectors, we anticipate that nanotechnology SMEs will depart from idealized linear models (e.g. beginning with research, then proceeding through to development, prototyping, and manufacturing for end markets). For example in the linear model one would expect publications and government grant awards to be associated with the research phase and so to be found near the beginning of the process. For firms engaged in iterative processes involving learning about customer needs and modifying the technology in response, we might expect to find publications and grants also in later, commercialization stages. Similarly, patenting might be expected to follow publication in the US, given the 12-month period available to file for patent protection after a disclosure. However, in practice, publication may follow patenting, particularly if a firm is targeting international markets with different patent protection rules or seeking to control the disclosure of potential intellectual property. Moreover, we would expect to see shifts in these patterns over time as firms who fail at their first commercialization attempt revise accordingly. This will allow us to probe the conditions under which SMEs switch between different kinds of roles within the innovation system. In formulating variables to test proposition 1, we are particularly interested to identify key indicators of technology-oriented enterprise development, along with their timing and sequencing. These include such activities as research, publication and presentation, intellectual property acquisition or licensing, demonstrations, trials, and manufacturing, and to relate these to financial and partnership developments.

**Proposition 2. Nanotechnology SMEs will be influenced by their technological targets in the development of their innovation strategies.** Sectoral innovation systems have long been identified as important to the business strategies of SMEs. Sectors have different knowledge resources, technologies, customers, suppliers, financial networks, labor access, and other institutional characteristics that operate in global value chains. We expect the choice of commercialization model to bear some relationship to the type of nanotechnology pursued and type of business model used. For example, physical science-based SMEs in nanotechnology (including enterprises in nano-materials, nano-chemistry, nano-energy, and nano-electronics) will be more likely to focus on supply-chain positioning (selling materials and intermediates to larger companies) and to pursue government contracts. Life-science based SMEs in nanotechnology will be more likely to acquire venture capital to support application development and market entry and to adopt a patenting model for protecting innovations. We posit that innovation paths will differ according to the SME's sectoral membership. For testing proposition 2, we will use the variables developed for proposition 1, interacting them with additional variables to denote sectors and market positioning. Further discussion of the full set of variables we use in the study follows in the next section.

## 4. Methods

This paper builds on the use of keyword analyses of websites to understand corporate strategy in Libaers et al (2010) by adding a time dimension and industry focus. Our approach involves the use of web-scraping to track, analyze and understand innovations emerging from nanotechnology discovery, with a particular focus on the roles, innovation strategies, and success factors associated with SMEs engaged in nanotechnology innovation activities. Web-scraping involves identifying and mining the extensive and dynamic sources of information posted by SMEs which are available on the Internet, then – because this information is varied and unstructured – organizing and coding this information to discover patterns and relationships. Web-scraping has the advantages of being unobtrusive and up-to date, although also allowing the development of time-series data through the use of Web-archived material. As with responses to questionnaire surveys, SME web pages are self-reports, and not everything an SME does will be posted to the Web (just as companies may not disclose all they are doing in a survey or even a case study). However, in an era where response to surveys can be depressingly low but where the Internet is used as an essential tool for business communication, presentation and marketing, we suggest that web-scraping may be a valuable complement to existing methods of obtaining information about enterprise strategies. Web-scraping has been widely used in computer science applications and in certain social science works examining internet mediated treatment of emerging technologies (Ladwig et al 2010) and social responsibility (Groves 2010).

Lei and Cunningham (2006) employ a web-crawling technique to identify linkages among nanotechnology Web portals, although they do not substantively mine enterprise web page content as implemented by web-scraping. Katz (2006) proposes the use of web-based indicators drawn from page counts and linking for evaluation of large scale innovation systems, based on how the Internet affects innovation systems and vice versa. As found in Libaers et al (2010), we anticipate that web-scraping will be especially useful for investigating SMEs, since these firms have Web sites that tend to be smaller and more manageably analyzed.

In this section, we report on a pilot application of web-scraping to investigate the transition from research to commercialization for a set of nanotechnology SMEs and, in particular, to probe our propositions about enterprise innovation strategies. We draw on a December 2008 list of companies that have used the NNIN's facilities. The listed companies have engaged in nanotechnology R&D using NNIN instruments and materials, for example, atomic force microscopes, soft lithography, and nanoparticles or nanomaterials (NNIN 2011). To exclude large companies, we applied the Fortunate 1000 listing and used the complement to develop a sampling frame of 358 non-Fortune 1000 companies. We searched for the Web sites of these non-Fortune 1000 companies on the Internet (in mid-2010). To account for changes over time in website information, we obtained older versions of websites from the Internet Archive's Wayback Machine.[1] (This archive captures web pages at points in time and retains them in a searchable library, even after the original pages have been changed or deleted.) Of the 358 companies, 80 were not pursued after an initial round of investigation for reasons that included no findable web site (48), merged or acquired by another company (12), or out of business (4). Among the remaining 278, we selected a random sample of 30 web sites. Given nanotechnology's initial general purpose technology characteristics, we note that it subsumes several subindustries. Fifty percent of our sample was in the nanoelectronics domain, another 40 percent in the nanobiotechnology domain, and 17 percent was in the nanoenergy domain. The sampling frame has 67 percent in nanoelectronics and nanoenergy and 33 percent in nanobiotechnology (distinguishing nanoelectronics and nanoenergy was not done until after we selected the sample because overlaps between these two domains required further research.) The sample has a somewhat larger percentage of nanobiotechnology enterprises than does the sampling frame, although there are sufficient numbers for analysis

Our original notion for analyzing these 30 nanotechnology SMEs was to capture the text from these web sites into a large file (recording original posting dates), then to analyze the resulting text using a set of keywords and NVivo software.[2] We tested this approach with two SMEs, developing text-based information from the current web site and all prior web sites in the Wayback Machine. However, this approach was difficult to scale in part because there was much incremental change on the web pages that had to do with small enhancements in presentation. In addition, there were personnel name changes that were difficult to synthesize for impact on commercialization. Ultimately we determined that the best way to analyze the information would be to flag important transitions in two areas: (1) product development information and (2) financing information. Taking into account all the web pages over time (in the Wayback Machine) for each of the 30 companies under analysis, we found that product transitions were present in 96 web pages from 1996 to 2010 and financial transitions were present in 43 web pages from 1999 to 2010. We coded these transitions into a series of variables covering product transitions. (See Table 1.) We also coded linearity in product and financial development, based on whether the company had followed what might be viewed as an idealized sequence of events (discussed in the next section). The ratio variables used in the study are based on the presence or absence of core elements of targeted text. Table 2 presents descriptive statistics for the full set of variables as well as year and sector.

[INSERT TABLE 1 AND TABLE 2 NEAR HERE]

[1] Internet Archive, Wayback Machine, http://www.archive.org/web/web.php.

[2] QSR International, Nvivo 9, http://www.qsrinternational.com/products_nvivo.aspx.

The main work components and time required for web-scraping 30 company web sites are as follows. The process began with a four-week effort reviewing the 358 companies in the sampling frame to determine if these companies were still in operation and if they had web sites. Another several days was spent selecting the 30 company sample. We devoted roughly a month to an in-depth analysis of two pilot companies; this effort included downloading archived Web pages and piloting different search approaches. Two weeks focused on capturing transitions in products or funding and the years that these benchmarks occurred. Another week was dedicated to entering this information into a database for analysis and about two weeks were applied to analysis and writing. The effort included one graduate student working half time for about three months and three senior researchers involved for several weeks in guiding the process and analyzing the results.

## 5. Results

The results show that it is possible to discern the timing of various innovation phases and transition points of nanotechnology SMEs through the analysis of their current and archived web sites. For our sample of nanotechnology SMEs, the year of appearance for the first corporate web site ranged from 1996 to 2007. The typical (mean and median) nanotechnology SME posted its first corporate web site in 2002. In about half the cases, product pages appeared at the same time as the SME's initial corporate web site. In the other half, product web pages appeared one to nine years after the date of the corporate web site, with three years being the median and modal lag time between the appearance of a product web page and the initial corporate web site.

To examine our first hypothesis, we used an idealized linear model of research to conference (and maybe journal) paper to patent to product to product portfolio to manufacturing and scale up on the product side. We compared this idealized model with the sequences displayed by the firms. We found that more than 80 percent of our sample demonstrated some linearity in the order of appearance of product oriented milestones. Despite the broad appearance of linear milestones, important nonlinearities are evident. For example, there are a few instances in which we see conference presentations being announced after the research/patenting/product have taken place; presumably firms use conferences as a knowledge exchange mechanism to unveil and demonstrate the application rather than as a venue for gaining feedback on early research finding as is traditionally the case.

We conducted a similar comparison on the finance side, with an idealized progression from government research grant to venture capital to sales. Roughly two-thirds of nanotechnology SME web sites demonstrated some linearity in the order of appearance of financing milestones. One observed nonlinearity in financing was the role of government grant awards received not just for funding research in the early and middle stages of the innovation cycle but also for procuring products and technologies in the later stages. However, while there were examples of diversity in product development and financing approaches, our analysis indicated that many companies in our pilot sample followed a linear model. A more complete assessment of a larger sample of nanotechnology SMEs would be necessary to confirm the nature of these commercialization strategies.

The second proposition about sectoral differences in commercialization approaches was examined through hierarchical cluster analysis. The aim of this analysis was to uncover potential latent patterns in commercialization approaches and compare the results across the three types of nanotechnology SMEs in our sample: nanoelectronics, nanobiotechnology, and nanoenergy. We used the variables indicated with a single asterisk in Table 2 in the cluster analysis because these variables had fewer missing cases and more variation in response. The hierarchical cluster analysis uses the companies as the cases and groups them in phases, drawing on the characteristics of the cases; eventually the cases end up as a single cluster. We used Ward's clustering method and squared Euclidean distance to specify similarities. Given the exploratory nature of this analysis, we based the selection of the number of clusters on the criterion to have the most parsimonious solution that still yielded a reasonably balanced number of cases for each cluster. We used the dendogram in Figure 1 to help us visualize this breakpoint. We first looked at the three-cluster solution, but rejected it because it classified more than half of the companies into a single cluster. We ultimately retained the four-cluster solution – represented by the dotted line in Figure 1 – because it produced a more balanced result than the three-cluster solution while still being relatively parsimonious.

[INSERT FIGURE 1 NEAR HERE]

One way we may interpret the four clusters is based on industry membership. The industry breakdowns in Figure 1 indicate that the three industry groups are not located in three separate and distinct clusters. The first cluster is composed of half nanobiotechnology and half nanoelectronics SMEs. Nanoelectronics represents the largest number of SMEs in the second cluster, but this cluster also has one energy and three nanobiotechnology SMEs. The third cluster consists mostly of nanobiotechnology companies but it also has one nanoelectronics company. The fourth cluster is a mix of nanoelectronics and nanoenergy companies. Thus, although these industry groups cross cluster boundaries, especially true of nanoelectronics, the clusters do have certain industry group characteristics. Cluster one is a mix of nanoelectronics and nanobiotechnology, cluster two a mix of all three groups, cluster three primarily nanobiotechnology companies, and cluster four nanoenergy (along with nanoelectronics companies).

Another way to interpret these clusters, in addition to industry group membership, is to examine the distribution of variables across these clusters. Table 3 shows mean or percentage values for several product and finance variables. Cluster one has relatively recent company website and web page creation years. SMEs in this cluster are most likely to rely on partnerships with other companies (mostly outside the United States) for product development. This cluster also has the highest percentage of firms that have raised capital through an initial public offering (IPO) or investors. Cluster two SMEs have more internet history than does cluster one. Firms in this cluster are also least likely to follow an idealized linear model in their product development approach. Cluster two has the highest percentage of references to financial sources such as venture capital and government grant awards. Cluster two firm web sites also are most apt to refer to patents and other intellectual property, publications, and participation at conferences and symposiums. Cluster three firms are the most recent. They tend to have the latest company website and web page years. Based on the information on their web pages, these firms follow an idealized linear product model in their product development process. SMEs in cluster three are the most likely of any of the four clusters to mention research advances on their website. SMEs in cluster four have the earliest company website and product web page years. Cluster four firms also follow an idealized linear product development model. Cluster four firms are most likely to report customer sales on the website. The use of IPO for fundraising among cluster four firms is at the same level as for cluster one firms.

In summary, this exploratory study has observed that there is considerable nanotechnology activity in SMEs at key commercialization product and financing transition points. This activity seems to adhere to the idealized linear product development model for the most part. There is also evidence of departure from sectoral models of innovation in nanotechnology SMEs. In spite of the constraints of the exploratory character of this work, we summarize and discuss the implications these findings below.

[INSERT TABLE 3 NEAR HERE]

## 6. Conclusions

Even as the field of nanotechnology experiences rapid growth, the movement from discovery to innovation cannot be taken for granted. Too often, innovative technology is assumed to automatically translate into successful commercialization and societal benefit. It is rarely so straightforward. In this paper, we argued that more attention is required to the end stages of the innovation process, in particular to better comprehend the wide range of innovation models that companies in emerging industries adopt and the dynamic evolution of their approaches. To do this, we must transcend the limitations of patents, publications, surveys and interviews. This research has used web-scraping methods applied to innovation models in nanotechnology SMEs.

This analysis is limited in examining 30 nanotechnology SMEs. The SMEs were associated with one of the major US nanotechnology programs for access to infrastructural support. The small size and source of the sample should be kept in mind when interpreting the results. On the other hand, each SME had multiple pages of web-based information that went back in some cases more than 10 years. Much potential exists for extending this method to larger sample sizes and examining relationships between the variables through regression models. In subsequent research, opportunities can be developed to triangulate and validate corporate web-sourced information, using other secondary databases and sources of primary information.

Two propositions underpinned our analysis. The first involved the extent to which nanotechnology SMEs depart from an idealized linear model in their transitions from research to innovation. Although there was some diversity, the results showed a level of linearity in product transitions and financing transitions that was unexpected. There were some exceptions. For example, the ongoing appearance of government funding departs from the view that public funds should be targeted to seeding high technology enterprise research, while the use of dual funding (government grants and procurement) is a topic that could be further examined by capturing and cross-analyzing information from pertinent grant programs.

The second proposition highlighted differences by sector through exploratory cluster analysis. The results indicated a four cluster solution, with two clusters reflecting industry specializations toward nanobiotechnology and nanoenergy and another two clusters indicating more general cross industry patterns. At least one nanoelectronics firm was located in each of the four clusters. Although this prominence of nanoelectronics is not completely surprising given that this subfield comprises half of the sample, it also suggests that nanoelectronics may be a foundational sector with relationship to other nanotechnology subfields.

At the same time, the clustering of product and finance approaches suggests that US nanotechnology SMEs adopt approaches that work for their firm even though these approaches may differ from those taken by their counterparts in similar subfields. Relatively older nanotechnology SMEs will adopt a customer sales approach to commercialization. Some newer nanotechnology SMEs will have a strong research orientation, which is consistent with Autio's observations about science-driven new technology-based firms. (Autio 1997). Other newer nanotechnology SMEs will seek shareholders and partnerships with larger companies to move their innovations forward. We further examined the nature of the partnerships in the web pages and found that most are with Asian and European multinationals rather than with large domestic US companies. In addition, a fourth approach involves acquisition of varied funding sources – both private venture and investment sources and government grants and contracts – as well as ongoing pursuit of intellectual property, publications and conference and trade show presentations. These results bring to mind that nanotechnology SMEs are indeed adopting divergent strategies as they transition from discovery to commercialization.

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**Figure 1. Hierarchical Cluster Analysis Dendogram**

(x axis represents the number of clusters)

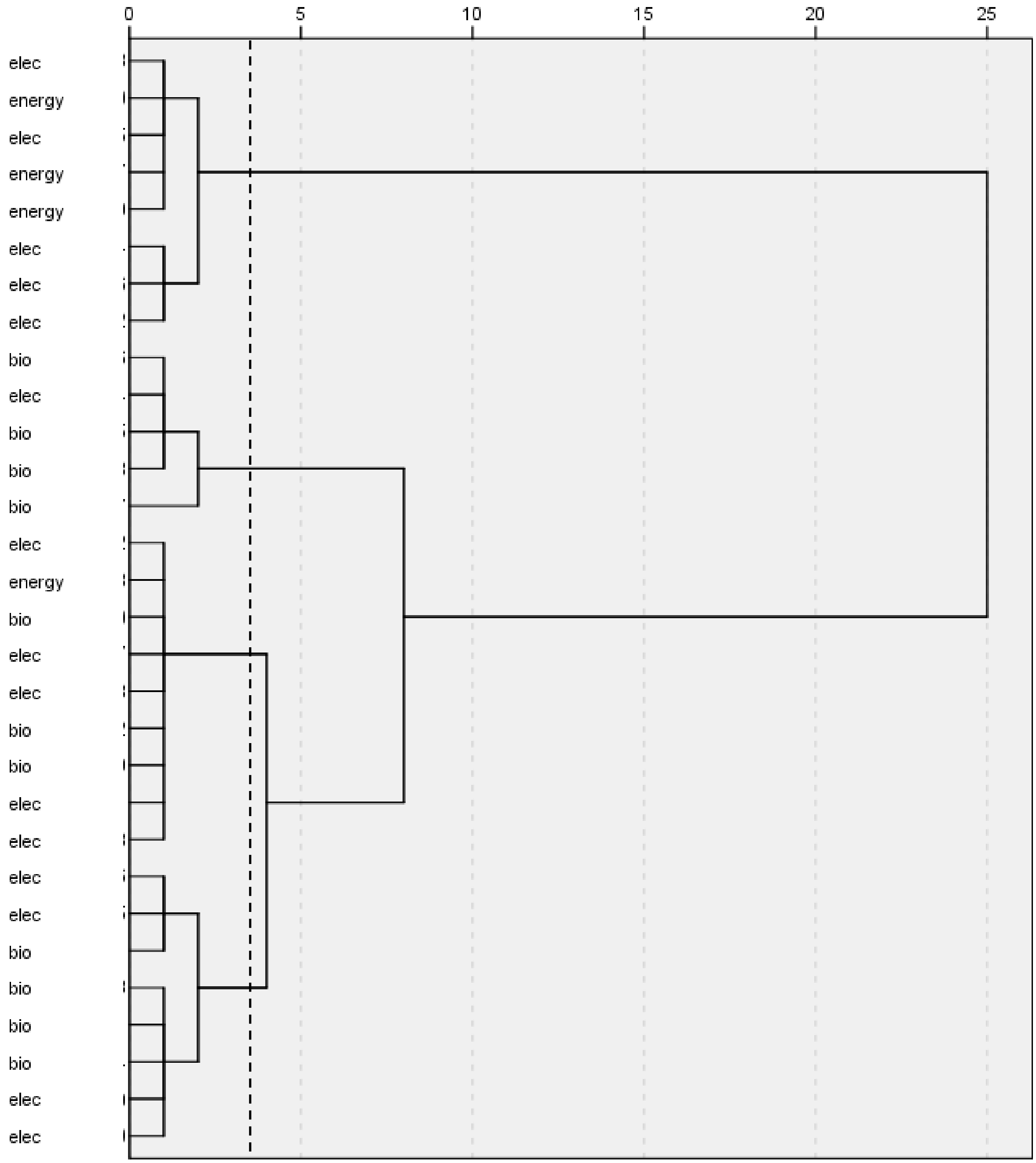

**Table 1. Variables, Key Terms and Operationalization**

| Variable | Terms / Operationalization |
|---|---|
| Conference/Symposium | Conferences, symposiums, trade shows |
| Patent/Trademark | Patent application or grants or pending, copyrights, trademarks |
| Research | Review of various research advances |
| Publication | Review of references to various peer reviewed scholarly articles |
| Demonstrations | Demonstration along with terms such as conferences, symposiums, trade shows |
| Pre-Clinical Trials | Pre-clinical trials, animal studies and related |
| Clinical | Clinical trials, human trials and related |
| Manufacturing | Manufacturing, production facility. |
| Venture Capital | Venture capital, series A funding and related |
| Partnership | Research and development, R&D and partnerships |
| Government Contract/Grant | Contracts or grants along with the names of federal or state agencies |
| Investors/General Funding | Investment, investors, finance, and related |
| General Revenue | Revenue |
| Private Contract | Review of contractual relationships with another company |
| Customer Sales | Sales |
| IPO/Shareholder | Initial public offering, IPO, investors, stock |
| Purchase Agreement | Purchase agreement |

**Table 2 Variable descriptive information, pilot sample of nanotechnology SMEs**

| **Years** | **Mean** | **N of firms** | **Std. dev.** |
|---|---|---|---|
| Founding year | 1997 | 27 | 11.1 |
| Year of first web site* | 2002 | 30 | 3.3 |
| Year of first product site* | 2004 | 30 | 4.2 |
| Year of first financial information | 2004 | 21 | 3.0 |
| **Technology Area** | | **N of firms** | **% of firms** |
| Nanoelectronics* | | 15 | 50% |
| Bionanotechnology* | | 12 | 40% |
| Nano energy* | | 5 | 17% |
| **Cycles** | | | |
| Linearity in Product Cycle* | | 26 | 87% |
| Linearity in Funding Cycle** | | 14 | 66% |
| **Financial** | | | |
| Venture Capital* | | 12 | 40% |
| Partnership* | | 11 | 37% |
| Government Contract/Grant* | | 9 | 30% |
| Investors/General Funding* | | 8 | 27% |
| General Revenue* | | 4 | 13% |
| Private Contract | | 3 | 10% |
| Customer Sales* | | 3 | 10% |
| IPO/Shareholders* | | 2 | 7% |
| Purchase Agreement | | 1 | 3% |
| **Product** | | | |
| Research * | | 17 | 57% |
| Conference/Symposium* | | 17 | 57% |
| Patent/Trademark* | | 16 | 53% |
| Publication* | | 6 | 20% |
| Demonstration | | 5 | 17% |
| Preclinical Trial | | 3 | 10% |
| Manufacturing Facility | | 2 | 7% |
| Clinical Trial | | 2 | 7% |

Source: Web-scraping of current and archived web sites
*Used in cluster analysis
**9 nano SMEs lacked funding references in their web pages

**Table 3 Product and Finance Variables by Nanotechnology SME Cluster**

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|
| **Technology area (# SMEs)** | | | | |
| Nanoelectronics | **4** | 5 | **1** | 5 |
| Bionanotechnology | **4** | 3 | **4** | 0 |
| Nano-energy | **0** | 1 | **0** | 3 |
| **Variable** | | | | |
| First year of company website (mean) | **2005** | 2001 | **2006** | 1998 |
| First year of product web page (mean) | 2006 | 2004 | **2010** | 1998 |
| Linearity in product line (proportion) | .88 | .67 | **1.00** | **1.00** |
| IPO/shareholder (proportion) | **.13** | .00 | .00 | **.13** |
| Partnership (proportion) | **.50** | .44 | .00 | .38 |
| General revenue (proportion) | .00 | .11 | .00 | **.38** |
| Venture Capital (proportion) | .38 | **.56** | .20 | .38 |
| Government Contract/Grant (proportion) | .13 | **.56** | .40 | .13 |
| Customer sales (proportion) | .00 | .11 | .00 | **.25** |
| Investors/General Funding (proportion) | .38 | **.44** | .20 | .00 |
| Research (proportion) | .38 | .78 | **1.00** | .25 |
| Patent/Trademark (proportion) | .63 | **.67** | .60 | .25 |
| Publication (proportion) | .13 | **.44** | .00 | .13 |
| Conference/Symposium (proportion) | .50 | **.78** | .20 | .63 |

N of cases=30. The highest proportion or mean year across the four clusters is highlighted.