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Nanotechnology documentary standards

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Abstract This paper adds to the nascent economics literature about nanotechnology by estimating industry's benefits and costs for the early investments in documentary standards that support the commercialization of nanotechnology, by identifying barriers to the successful development and use of the nanotechnology documentary standards, and by providing public policy recommendations to overcome the barriers.

Keywords Nanotechnology · Documentary standards · Innovation · Barriers to technology · University-industry partnerships

JEL Classification O320 · O330 · O380

1 Introduction

This paper presents evidence about the benefits and costs of nanotechnology documentary standards and makes policy recommendations based on the evidence.[1] Nanotechnology is an important general-purpose technology (Youtie et al. 2008) for the twenty-first century.[2]

[1] The report, Leech and Scott (2015), provides detailed discussion and references about nanotechnology documentary standards and the emerging nanotechnology industry, with many of the references cited coming from direct participants in the nanotechnology community of researchers and policy makers. In this article, we focus on the material in the report that is new to the literature and is based on our survey of the nanotechnology standards developers and users.

[2] Salamon et al. (2010) explain that nanotechnology applies nanoscience—the knowledge about the manipulation of matter on an extraordinarily small scale with dimensions measured in a fairly small number of nanometers. A nanometer is a billionth of a meter. Nanomaterials are <100 nm in size in at least one

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Documentary standards are a part of the national and international innovation system; they are an important part of the public–private technological infrastructure that enables the development and diffusion of new knowledge and know-how that generates economic growth and development.

Documentary standards are precisely written agreements that result from a consensus-making process concerning a set of technical issues ranging across terminology, measurement, and labeling. The documentary standards enable the successful use of physical measurement standards in industrial research and development (R&D) efforts and the resulting commercialized products and services. The U.S. standards system is highly decentralized, primarily voluntary, private sector and market-driven; the U.S. federal government participates as one of many stakeholders in the standards development process.[3] Such standards support effective development of a technology and its wide application. Nanotechnology development and application are in their early stages; and therefore, the documentary standards studied in this paper are regarded as early-stage standards that are formulated via consensus process and set down early in the life cycle of the development of nanoscience and nanotechnology based products and services.

Nanotechnology is being applied commercially in applications such as nanoscale titanium dioxide, gold, silver and copper additives that improve the performance of plastic, paint, and other bulk materials (Rashba and Gamota 2003). Other products include nanoscale drug delivery vehicles and carbon nanotubes for field emissive displays. According to National Center for Manufacturing Sciences (NCMS) survey results, applications include nanomaterials (e.g., nano-structured catalysts, carbon nanotubes, quantum dots, nanowires and dopants), complementary metal-oxide semiconductor (CMOS)-based electronics and manufacturing processes, other silicon-based energy conversion processes, thin-film coating processes, closed-environment handling systems, nanotechnology-enabled miniaturized biomedical and diagnostic devices, and designer drugs and targeted therapies (NCMS 2010).

Salamon (2013) observes that, today, nanoproducts are coming to market too fast for environmental sciences and toxicological sciences to keep up, and that is creating gaps in the industry's ability to analyze risk. Closing those gaps is one of the objectives for standards developers.

The value chain for nanotechnology and the emerging nanotechnology industries is complex. As discussed in Leech and Scott (2015, pp. 15–17), the applications in aerospace, energy, electronics, autos, construction materials, coatings, textiles, personal care, packaging, and medicine are based on upstream activities of nanomaterial synthesis that require raw materials and ultimately the knowledge generated in university research. Interacting

Footnote 2 continued
direction, and nano-objects are materials with at least one dimension in the nanoscale range of 1–100 nm, and a nanoparticle is a nano-object with all three dimensions in the nanoscale range and with a property not exhibited by the bulk material.

[3] *ISO/IEC Guide 2: 2004, Standardization and related activities—General vocabulary*, provides a general overview of standards. There are two broad types of standards—physical measurement standards and documentary standards. The National Institute of Standards and Technology (NIST) develops, maintains, and disseminates U.S. national physical measurement standards traceable to the international system of measurements. Documentary standards are written agreements among the producers and users of products and services; the agreements contain precise criteria for specified characteristics ensuring that materials, products, personnel qualifications, processes, and services are adequate for their purpose, compatible or interchangeable if necessary, protect the environment and the public health and safety. Documentary standards can specify product characteristics, define processes and systems, or specify knowledge, training and competencies for specific tasks. See also Breitenberg (2009).

with all the stages of the value chain are independent testing laboratories, manufacturers of measurement instruments, the standards development organizations (SDOs), regulatory agencies, NIST, and other Federal laboratories.

The literature has documented the importance for nanotechnologies of university-based science and university–industry collaboration (for example, Libaers et al. 2006; Youtie and Shapira 2008; Thursby and Thursby 2011; Coccia et al. 2012; Ponomariov 2013), of appropriate university and public policies toward research, R&D, and technology transfer (for example, Mowery 2011; Bozeman et al. 2008; Shapira et al. 2011). In this paper, we emphasize that documentary standards for nanotechnology play an important role and are yielding benefits to the evolving commercialization of nanotechnology applications, yet there is a disconnect between industry and the university community regarding documentary standards, and also many free riders early in the standards process.

Documentary standards create positive externalities—benefits for producers and consumers who do not have to pay for those benefits. The documentary standards have the characteristics of a public good; they are, to a large extent, goods that are nonrivalrous and nonexcludable. As Tassey (2015) explains for technology standards in general, sound public policies are needed to address the resulting market failures and improve market outcomes.

Bozeman et al. (2008) have surveyed the population of North Carolina firms using nanotechnology and identified barriers—lack of access to early-stage capital and to university equipment and facilities—to the successful diffusion of nanotechnology. Based on our findings from an evaluation of industry's early investments in documentary standards to support the commercial applications of nanotechnology, to Bozeman et al.'s list of barriers we add the need to overcome the disconnect between universities and industry in the development and use of nanotechnology documentary standards and to address the free-rider problem in the development of documentary standards. Bozeman et al. make suggestions for public policies—state governments acting as venture capitalists and also providing incentives to universities to share equipment and facilities with nanotechnology firms—to overcome the barriers to nanotechnology diffusion. Because documentary standards are important for the diffusion of nanotechnologies, we add recommendations for public policy to overcome barriers to the development of documentary standards in the nascent nanotechnology industries.

Section 2 describes the surveyed sample of organizations developing documentary standards to support the commercialization of nanotechnology. Section 3 provides our evaluation of the returns to the early investments in nanotechnology documentary standards. Section 4 explains the different perception of universities—a perception different from the views of our industrial respondents—about the importance of the nanotechnology documentary standards. Section 5 concludes and offers recommendations for public policy to overcome the barriers to the development of nanotechnology documentary standards.

2 The survey sample

The major nanotechnology standardizations efforts were initiated in the early to mid-2000s by ASTM International, the European Committee for Standardization (CEN), the International Electrotechnical Commission (IEC), and the International Organization for Standardization (ISO). For this study, we surveyed participants in the nanotechnology standards development process of the technical committees of three of these organizations.

The three committees and their activities are as follows.[4] ASTM International, Technical Committee E56 (TCE56) on Nanotechnology was established in 2005 and focuses on terminology standards, definitive practices, test methods, and inter-laboratory studies. Subcommittee standardization activities include informatics and terminology; characterization of physical, chemical and toxicological properties; environment, health and safety; and consumer products enabled by nanotechnology. IEC Technical Committee 113 (TC113) on nanotechnology standardization for electrical and electronic products and systems began with the establishment in 2005 of the Advisory Board on Nanotechnologies. The Board focuses on standards development relevant to electrical and electronic products and systems in the field of nanotechnology. Standardization activities include terminology and nomenclature as well as measurement and characterization—both jointly with ISO TC229, and assessment of performance, reliability and durability of nanotechnology-enabled aspects of electronic components and systems. ISO Technical Committee 229 (TC229) was established in 2005 with a broad scope for addressing standardization issues about the control of matter and processes at the nanoscale and use of the properties of nanoscale materials to create improved materials, devices, and systems. The standardization activities include terminology and nomenclature as well as measurement and characterization—both jointly with IEC TC113; health, safety and environment; and materials specification. Task groups also address issues about the consumer and societal dimensions of nanotechnology, including sustainability issues.

Guided by advice from ASTM International and the U.S. technical advisory groups of the IEC and the ISO, information from the NanoBusiness Commercialization Association and the National Nanomanufacturing Network, and the list of university research organizations funded as part of the U.S. National Nanotechnology Initiative (NNI), the survey was e-mailed in June 2013 to potential respondents representing private sector, public sector, and university organizations that have been involved in the development of nanotechnology documentary standards. Although there were informative e-mail exchanges with respondents from many more organizations, we obtained survey responses from 26 organizations—13 were from industry respondents, 9 from university respondents, and 4 from government agencies. All 13 of the responding industry organizations were SDO participants—that is, there were no responses from the potential industry respondents who did not participate in the SDO nanotechnology standards development activities. The responses from the respondents based in universities and in government were incomplete and did not allow quantitative estimates of benefits and costs, but the partial responses are useful for qualitative inferences about the nanotechnology standards process.

Of the 26 organizations responding, 21 respondents identified the nanotechnology standards that were most significant in terms of benefits created for their organizations. A list of the nanotechnology standards published by the ASTM International, IEC, and ISO technical committees was provided as an appendix to the survey instrument. From 2005 through 2012, there were 10 nanotechnology standards published by ASTM TCE56, 4 by IEC TC113, and 26 by ISO TC229. Each respondent was asked to examine the list of the 40 nanotechnology standards and to identify the five that were the most significant for the respondent's organization. For the standards that were indicated by more than one respondent, Table 1 shows the ranking of the top five (including ties—for example, three standards were top five picks for six of the 13 industry respondents and are tied for third place among the most significant standards for the industry respondents) standards based

[4] The overview of the SDOs is based on Jillavenkatesa et al. (2012).

Table 1 Standards among the top five (including ties) for impact on the organization's activities

All respondents (n = 21)	Industry respondents (n = 13)	Documentary standard title
13	8	ISO/TS 80004-1:2010 – Nanotechnologies – Vocabulary – Part 1: Core terms
14	7	ISO/TS 27687:2008 – Nanotechnologies – Terminology and definitions for nano-objects – Nanoparticle, nanofiber and nanoplate
10	6	ISO/TR 12885:2008 – Nanotechnologies – Health and safety practices in occupational settings relevant to nanotechnologies
–	6	ISO/TS 80004-4:2011 – Nanotechnologies – Vocabulary – Part 4: Nanostructured materials
–	6	ISO/TR 13121:2011 – Nanotechnologies – Nanomaterial risk evaluation
8	5	[ASTM E56] E2535-07 Standard Guide for Handling Unbound Engineered Nanoscale Particles in Occupational Settings
7	5	ISO/TR 11360:2010 – Nanotechnologies – Methodology for the classification and categorization of nanomaterials
7	5	ISO/TR 13014:2012 - Nanotechnologies - Guidance on physicochemical characterization of engineered nanoscale materials for toxicologic assessment
–	4	ISO/TS 12805:2011 – Nanotechnologies – Materials specifications – Guidance on specifying nano-objects
7	–	[ASTM E56] E2456-06 Standard Terminology Relating to Nanotechnology

on a simple count of the number of respondents that chose each standard as one among its most significant five.

For the group of all types of respondents—from industry, academia, and government—standards about vocabulary, terminology, and classification, and about health and safety are of greatest importance for the respondents. Looking at the responses underlying Table 1, materials characterization and specification are more important to industry than to the university respondents. In Sect. 4 of the paper, we use the underlying responses to provide details about the different perceptions of universities and industry about the importance of the nanotechnology documentary standards. The difference in how universities and industry value standards for materials characterizations and specifications is especially significant because of the importance of materials characterizations and specifications for technology transfer of knowledge from more basic research to industrial applications.

In background interviews, technical committee members representing industry, universities, and government organizations discussed the ways documentary standards make a difference in their organizations, and from those discussions a list of nanotechnology-related activities emerged. To avoid asking too much of respondents, simply the information about the percentage of benefits in each of the top three categories was collected to indicate the areas of greatest importance. Each survey respondent was asked to determine the three activities in the list that within their organization were most affected by nanotechnology standards. Each respondent was asked to estimate the percentage of all benefits—for the organization from the adoption of nanotechnology standards—associated with each of the three most significant activities. For the 13 industrial respondents, Table 2 identifies and ranks the activity areas by the percent of total benefits accounted for by each activity.

Respondents were asked: "For the 3 activities selected in the Nanotechnologies-Related Activities Table above, provide a few sentences describing how the existence of nanotechnology standards changed the processes that resulted in benefits to your organization." Some respondents briefly described how the existence of nanotechnology standards changed the processes within their organizations and resulted in efficiencies and quality improvements. Their comments reflect the ranking in Table 2, but also the breadth of the ways standards have an economic impact.

Many respondents highlighted the importance to their organizations of planning and implementing environmental/health/safety procedures. Accordingly, respondents claim that guidance standards related to risk while working with nanomaterials were helpful in establishing internal practices to protect employees from potentially harmful exposure to nanomaterials, in facilitating global corporate meetings concerning new risk management

Table 2 Industry respondents' activity areas most affected by documentary standards[a]

Nano-related activities	Percent of all benefits (average of respondents reporting the activity as in the top three)	Number of respondents reporting the activity as in the top three	Range for percent of all benefits
Safety & environmental monitoring & risk management	39	8	10–100
Product design & development (excluding regulatory compliance)	38	8	20–50
Pre-development R&D & knowledge acquisition	36	6	20–60
Marketing, market intelligence, & B2B networking	30	2	20–40
Contract negotiations	30	1	30
Quality assurance & control	20	2	10–30
Regulatory compliance, negotiations, & monitoring	18	4	10–33
Equipment adaptation & acquisition justification	17	3	10–20
Worker & student training	15	2	10–20
Intellectual property due diligence	10	2	10

[a] Respondents were instructed: "[For the] Nanotechnologies-Related Activities Table…, select the top 3 activities within your organization that you judge have been most affected by nanotechnology standards and estimate the percent of all the benefits from nontechnology standards that each of these 3 activities represent. *(For example, your top 3 activities could each account for 33 % of all benefits equally, leaving very little benefits accounted for by other activities; or they could account for 50, 30 and 2 %, leaving the unspecified 18 % of all benefits spread among the remaining activities.)*"

procedures, in the development of new products, in safety and environmental monitoring and handling of nanomaterials, in training workers in proper protocols and data handling, in detailing a prudent approach to workplace safety and product stewardship, and in enabling the improved design of laboratory and manufacturing space.

Others stressed that terminology standards dramatically improved communications internally and externally. Some say that consistency in terminology ensures that all participants, regardless of the diversity of their goals and perspectives, know what is meant by the defined terms. Others stress that standard terminology supports *correct* communications, that participants know what is being communicated, and also that what is being communicated is correct.

Still other industry participants benefit from the role of early nanotechnology standards to set specifications and materials usage in production quality assurance and in developing quality assurance plans.

Respondents stress several facets of the market intelligence value of the standards development process. It allows them to keep a focus on applications that matter to them, to know the places where nanotechnology is being used, and to support the product design and development that potential customers require.

Finally some respondents understand current standards as a step on the path to regulation that will evolve slowly as legislation addresses the emerging nanotechnology industries. In all, SDO members representing industry appear to be focused on gaining a firmer foothold in an ambiguous economic and regulatory environment. They appear to be very future-focused, perhaps expecting to enjoy early-mover advantages in the marketplace. They are anticipating the market, concerned to reduce the technical and market risks associated with burgeoning markets, and concerned about the effectiveness and correctness of communications within their sometimes large and diversified organizations but also between their organizations and other stakeholders.

3 Industry's benefits and costs

To gain insight about the benefits and costs of the early stage of development of nanotechnology standards, we examined the perspectives of the 13 industrial respondents, all of which are SDO participants.[5] The respondents estimated the economic impacts of the nanotechnology documentary standards published by ASTM E56, IEC/TC113, and ISO TC229 within the period from 2005 (when those standardization efforts began) through 2012. An appendix to the survey instrument provided the list of those standards, and the survey instrument with the list is available in Leech and Scott (2015) along with a detailed development of the estimated costs and benefits and the assumptions and methods used to translate the information provided by the respondents into the evaluation metrics.

Each of the respondents was asked the following counterfactual question:

> For the activity area in your organization that benefitted most from nanotechnology standards, what would it have cost your organization to perform those activities in

[5] The evaluation approach is consistent with the methods, described in Link and Scott (1998, 2011, 2012, 2013) used in the evaluation of NIST's investments in infrastructure technologies, although here the investments are only those of the SDO participants. Scott and Scott (2015) provide an alternative approach to the evaluation of the impact on industry of standards—an approach that may prove useful in evaluating the impact of nanotechnology standards once they have developed beyond the early documentary standards stage.

the absence of ATM E56, IEC/TC113, and ISO TC229 standards published between 2005 and 2012?

For purposes of benefit-cost analysis, the counterfactual costs that in the respondent's estimation would have been incurred in the absence of the relevant nanotechnology documentary standards are interpreted as the economic benefits accruing to the respondent's activity that benefited most from the standards. Each respondent's costs for the documentary standards are the costs of participating in the SDO technical committees plus the additional pull costs to implement the standards.[6] Industry survey respondents provided a range of information from which time series of costs and benefits were constructed. The number of full-time equivalent (FTE) personnel dedicated to the activity most affected by standards (see Table 2 for the activity categories) was estimated.[7] Also estimated was the multiple of these FTEs that would be incurred in 2012 in the absence of the documentary standards.[8] This counterfactual multiple was used to estimate the benefits—the avoidance of additional personnel costs—companies derived from the use of nanotechnology documentary standards in the activity that benefited most from the use of the standards.

Respondents' estimates of the average annual growth rate, over the period from 2005 through 2012, for the activities benefiting most from nanotechnology documentary standards ranged from 0 to 100 %. The estimated growth rates were used to derive, from the benefit of avoided personnel costs reported for 2012, the benefits in the earlier years of the 2005–2012 period. The benefits in terms of hours of personnel time saved were converted to dollar costs using the annual compensation of full-time workers engaged in those activities.[9]

One respondent estimated that there would have been a delay in some sales had important standards been delayed. That additional source of benefits was not factored into the estimated benefits, so there is an unmeasured benefit from avoiding a delay in sales.[10]

The cost of SDO technical committee participation was derived from estimates of the average annual time each respondent devoted to technical committee work and each respondent's estimated annual compensation for the employees involved.[11] To this was added each respondent's estimate of "pull costs" to derive the total cost to respondents'

[6] Communications with some respondents indicated that their estimates of pull costs included significant elements of direct operational costs. Adjustments were made to these high estimates based on communications with other respondents whose estimates, upon further investigation, were found to be a more accurate reflection of "pure" pull costs. Pull costs are indirect costs; the costs of identifying, acquiring, and implementing ("pulling in") information or know-how from external sources. See Link (1996).

[7] For the 13 respondents, the average was 3.19 FTE with a range between 0.05 and 20 FTEs.

[8] The 13 respondents reported multiples as high as 3 times with the average being 1.45 times more.

[9] For the 13 industrial respondents, that reported annual compensation averaged $137,000 for the fiscal year 2012.

[10] Considering a technical committee's standards as a group, survey respondents estimated that NIST's participation in a technical committee's deliberation process shortened a standard's publication time by an average of 20 weeks. Since this economic impact assessment focuses on industry's costs and benefits, this time saving was not developed into an estimate of the social return on the investment of NIST's time in support of technical committee activities.

[11] The average of the 13 industrial respondents' average annual time for technical committee work was 218 hours per year, ranging from 40 to 500 hours. The average for the 13 respondents' annual compensation was $159,000, ranging from $45,000 to $250,000.

organizations of participating in the technical committees' standards development process.[12]

Respondents estimated the scale of their own company's benefits from documentary standards relative to those of their direct competitors. The information about each respondent's share of the benefits was used to estimate benefits for the "industry"—that is, the part of the emerging nanotechnology industries—in which each respondent operates. The 13 respondents operate in different areas of the emerging nanotechnology industries, and each respondent's industry is assumed to include the responding company (or division in some cases) and its direct competitors in a particular segment of the nanotechnology supply chain.

Industry beneficiaries include SDO participants and "free riders." The latter beneficiaries do not participate in the SDO process. To understand the potential for beneficial spillovers from the SDO nanotechnology standards development process, benefits and costs are estimated for each respondent's direct competitors. Some of those direct competitors are also SDO participants. Their benefits from the nanotechnology standards will be similar to those of the respondents. Their cost will include both SDO participation costs and pull costs. However, some competitors will be free riders for whom the costs of using the nanotechnology standards will be their pull costs alone. The survey asked the respondents to report the number of their direct competitors in nanotechnology-related research or in the sale of nanotechnology-related services or products to major customers. Respondents also reported the number of direct competitors that were most similar to themselves in terms of the benefits and costs of nanotechnology standards. On average, the 13 industrial respondents reported that the group of direct competitors who were most similar constituted 34 % of the total number of direct competitors.

To estimate the spillover of benefits to non-participants in the SDO nanotechnology standards development process (free riders), it is assumed that all of the competitors of each of the 13 respondents enjoy the benefits of nanotechnology standards and that the 34 % of the respondents' direct competitors that are most similar to the respondents in terms of the realization of benefits and costs are also participants in the SDO nanotechnology standards development process. The remaining 66 % of the competitors are assumed to be free riders.

Table 3 provides a time series of the benefit estimates for the period from 2005 through 2012. Survey respondents estimated benefits for only the activity that benefited the most from the use of nanotechnology standards, yet the respondents each reported that many of their activities benefited from their adoption of nanotechnology standards. Without

[12] The pull costs ranged from $975 to $66,000 for one-time labor costs and from $1000 to $4100 for one-time material costs. All but one of the 13 respondents were technical committee members during the study period (the one became a member in 2013) and, therefore, participated in the development of the standards. From the perspective of the respondent's sponsoring company, technical committee cost associated with the development of standards could be construed as a type of pull cost. However, for the participants, their technical committee costs were reported and then any separable, additional "pull costs" (apart from the costs of participation in the technical committee) were reported and the two categories of cost are combined into a total cost for each respondent. Companies that benefit from the nanotechnology standards but do not participate in technical committee activities are free riders and do not incur the costs of participating in the committee work to develop the standards, but they do incur pull costs. To estimate these, it was assumed that the temporal distribution of the non-participants' pull costs was identical to the temporal distribution of the separable pull costs reported by SDO-participating respondents (pegged to the earliest standard cited as most significant for the survey respondent's organization). The respondents' pull costs were multiplied by the average multiplier used to estimate benefits and costs of a respondent's close competitors from the benefits and costs of the respondent.

Table 3 Constant 2012 dollar industry benefits (2005–2012)

Year	Responding SDO participants' constant 2012 dollar benefits	Competitors' constant 2012 dollar benefits	Total constant 2012 dollar benefits
2005	0	0	0
2006	121,902	524,702	646,604
2007	888,151	1,354,483	2,242,635
2008	1,947,114	9,295,465	11,242,580
2009	2,273,934	10,478,988	12,752,923
2010	2,587,166	11,661,628	14,248,793
2011	3,049,332	13,407,336	16,456,668
2012	3,789,502	16,215,910	20,005,412

For the sake of survey simplicity, respondents were instructed to estimate benefits and costs in FY2012 dollars. These benefits and costs were spread over time according to the activity growth rate reported by the respondent, beginning with the earliest publication year of the high-impact documentary standards reported by the respondent. Variance in the yearly ratio of competitors' benefits to participants' benefits is due to variance in the timing of participants' benefits. The yearly variation in "industry" benefits then reflects the variation in benefits for different mixes of the parts of the emerging nanotechnology industries in different years

accounting for the benefits other than the one activity that benefited the most, the total benefits for the respondents' industries would be greatly underestimated. In the survey information used to create Table 2, each respondent reported the proportion of its total benefits received from the use of nanotechnology standards that accrued to the activity benefiting the most. That proportion averaged 0.495 (with a range from 0.30 to 1.0) for the 13 industrial respondents. So, on average across the respondents, the total benefits from using nanotechnology standards averaged twice the benefits received for the activity that benefited the most. Using the benefits reported for the activity that received the most benefits for each respondent, together with each respondent's information about that activity's proportion of the benefits for all of the respondent's activities, Table 3 shows the annual benefits of all activities for the 13 responding SDO participants (designated "Responding SDO Participants"). The respondents also reported the scale of their own benefits and costs relative to that of their direct competitors (both those who participated in the SDOs but did not respond as well as free riders, together designated "Competitors") and that allows the construction of the benefits and costs series for the competitors shown in Tables 3 and 4.

Table 4 shows the time series of costs for the 13 respondents and their competitors (SDO participating competitors and free-riding competitors). As explained above, in Table 4 it is assumed that 34 % of the respondents' direct competitors are SDO participants and have the same costs as the SDO participants with which they compete, while 66 % of the competitors would be free riders and would have only the pull costs associated with implementing the standards. If they all had the same costs, each item in the "Responding SDO Participants" cost column would be multiplied by the same ratio used to get the competitors' benefits in Table 3. But, given our assumptions, only 34 % will have all of those costs. Therefore, to estimate the costs of the SDO participating competitors the column of costs for the 13 respondents is multiplied by 34 % of the multiplier used for

Table 4 Constant 2012 dollar industry costs (2005–2012)

Year	Responding SDO participants' constant 2012 dollar costs	Competitors' constant 2012 dollar costs	Total constant 2012 dollar costs
2005	192,004	284,962	476,966
2006	198,844	296,227	495,071
2007	252,365	141,416	393,781
2008	279,302	460,699	740,002
2009	258,265	431,445	689,710
2010	266,325	560,172	826,497
2011	280,588	469,140	749,728
2012	341,413	751,075	1,092,488

each year in Table 3.[13] Then only pull costs for the other 66 % of the competitors are added, using 66 % of the yearly pull costs that were estimated for all of the competitors.

From the benefits shown in Table 3, the costs shown in Table 4 are subtracted to get the net benefits shown in Table 5. Competitors' net benefits are probably overestimated because the pull costs of the free-riding competitors have been estimated using the pull costs of the SDO participants. Actual pull costs for non-participants would be expected to be higher because non-participants in the SDO process would have to gain knowledge that a participant would have absorbed while participating in the SDO TCs. Table 6 breaks out the benefits and net benefits for the free riders.

Tables 5 and 6 provide the information needed to estimate the summary economic impact estimates reported in Table 7: net present value (NPV), cumulative net benefits, industry rate of return, and benefit-to-cost ratio (B/C).

Despite the very large economic impact found for the early-stage documentary standards, the estimates of economic impact shown in Table 7 are probably conservative because (1) there are unmeasured benefits of avoiding shortfalls in performance (such as a shortfall in sales) even if the firm incurs extra costs to compensate for the lack of nanotechnology standards, and (2) the percentage of competitors that are SDO participants has probably been overestimated.

The benefits of nanotechnology documentary standards are conceptualized as the dollar value of costs avoided because the industry has access to the standards. On average, nanotechnology-related activities would have cost industry respondents almost 50 % more in the absence of the standards. The costs incurred by developing and using the standards are the dollar value of hours Technical Committee members dedicated to the SDO consensus process plus the cost of pulling the information into their organizations and into the organizations of free riders.

The first impact metric shown in Table 7 (Net Present Value in 2005) uses the year the three nanotechnology SDOs were formally started as the base year and calculates the net present value of the project from the perspective of 2005. The NPV is the inflation-adjusted (real or constant-dollar) value of the net benefits (benefits minus costs) generated by the project over the course of the study period (2005–2012). If, in 2005, an SDO's leadership was trying to judge which of two or more projects (new TCs) would yield the highest economic return to the SDO, this is the kind of calculation they would have made. From an

[13] For 2005, 34 % of the Table 3 2006 multiplier is used.

Table 5 Constant 2012 dollar net benefits to industry (2005–2012)

Year	Responding SDO participants' constant 2012 dollar net benefits	Competitors' constant 2012 dollar net benefits	Total constant 2012 dollar net benefits
2005	−192,004	−284,962	−476,966
2006	−76,942	228,475	151,533
2007	635,786	1,213,067	1,848,854
2008	1,667,812	8,834,766	10,502,578
2009	2,015,669	10,047,543	12,063,213
2010	2,320,841	11,101,456	13,422,296
2011	2,768,744	12,938,196	15,706,940
2012	3,448,089	15,464,835	18,912,924

Table 6 Constant 2012 dollar net benefits to the free riders (2005–2012)

Year	Free riders' constant 2012 dollar benefits[a]	Free riders' constant 2012 dollar net benefits[b]
2005	0	−3972
2006	346,303	341,076
2007	893,959	883,399
2008	6,135,007	6,127,657
2009	6,916,132	6,889,343
2010	7,696,674	7,544,658
2011	8,848,842	8,799,157
2012	10,702,501	10,448,154

[a] Free riders get 66 % of the competitors' benefits shown in Table 3

[b] The net benefits for the free riders subtract their pull costs from their benefits. Their pull costs are 66 % of the pull costs estimated for the competitors

Table 7 Estimates of economic impact (constant 2012 dollars) for 2005–2012

Impact metrics	Responding SDO participants	Competitors	Free riders[b]	Total
NPV in 2005	8,837,538	42,032,301	29,093,297	50,869,841
Cumulative net benefits in 2012[a]	14,191,155	67,494,690	46,717,477	81,685,848
Industry rate of return	177 %	321 %	8758 %	270 %
Benefit-to-cost ratio	6.5	17	85	13
Present value of benefits in 2005	10,450,295	44,602,579	29,437,703	55,052,876
Present value of costs in 2005	1,612,756	2,570,279	344,406	4,183,035

[a] (Net Present Value in 2005) multiplied by $(1.07)^7$

[b] The exceptionally high return to the free riders is because they did not incur the SDO participants' costs that generated their benefits (see discussion in text)

economic perspective, the project (TC) with the highest industry-wide NPV would have been chosen.

The second impact metric (Cumulative Net Benefits in 2012 (2005–2012)) is intended to interpret the NPV of the net benefits that actually occurred as a result of the SDOs' efforts (NPV in 2005) from the perspective of 2012, rather than from the perspective of 2005. If the net benefits that actually accrued to the effort (NPV in 2005, approximately $51 million) were invested in 2005 and were compounded annually at the rate of the cost of capital used by the U.S. government to evaluate investment projects (7 %), the value of those benefits today would be approximately $82 million.[14]

The third impact metric (Industry Rate of Return) is similar to an internal rate of return calculation, another corporate finance technique used to judge the performance of an investment project. The modifier "industry" indicates that the value of this performance metric accounts for the benefits and costs that accrue to the industrial firms that have participated in or benefited from the work of the SDOs.[15] The industry's rate of return is the interest rate (also called the "discount rate") that would reduce the NPV in 2005 of the TC's efforts to zero and reduce the benefit-cost ratio to one—the investment would break even at that required rate of return. As a guide to making a decision on an investment project (private or public), if the industry's rate of return is higher than the discount rate, the project is acceptable because the project earns a rate of return greater than its cost of capital.

Finally, the benefit-to-cost ratio (B/C) is simply the ratio of the present value (PV) of benefits (2005–2012) to the PV of costs (approximately $55 million/$4.0 million). This value indicates that the real value of the benefits of the SDOs' efforts, industry-wide, exceeded the costs by a ratio of approximately 13:1.

These estimates can be considered conservative for reasons just explained. For comparison purposes, it is appropriate to recall a historically important analysis conducted in the mid-1970s. Economist Edwin Mansfield and his coauthors reported on the private rates of return and societal rates of return on private sector innovations. The private and social rates of return differ because of the "externalities" discussed earlier. Using a methodology similar to the one used in this assessment, Mansfield reported the median social rate of return (SRR, to which our industry-wide rate of return can be compared) for 17 private sector projects to be 56 %, ranging between 13 and 307 %.[16] To verify Mansfield's results, the National Science Foundation funded two other similar assessments (Foster Associates 1978; Robert R. Nathan Associates 1978), each examining an additional 20 private sector innovations. The median SRR for one of these assessments was 70 %, ranging between 0 and 371 %; the median SRR for the other was 99 %, ranging between 0 and 472 %. These SRRs can also be compared to the Industry Rate of Return of 270 % reported in Table 7.

[14] The government cost of capital is stipulated as seven percent in Office of Management and Budget (1992). For a discussion of the rationale of the seven percent discount rate, see Link and Scott (2011) and Office of Management and Budget (2003).

[15] "Industry Rate of Return" is adopted here to indicate the study focus on industry-wide costs and benefits, exclusive of other social costs (for example, NIST's costs of participating in the SDO activities) and benefits. Previous NIST reports have reported a similar metric, the "social rate of return" (SRR) that is an interpretation of the ordinary financial metric, "internal rate of return" (IRR) used routinely by industry to rank private sector investment projects. The "social" in SRR ideally measures the costs and benefits that accrue to all investors and beneficiaries, public and private.

[16] Concerning the historical importance of Edwin Mansfield's work see Scherer and Link (2005) and Link and Scott (2011, pp. 28–31). The assessment of 17 private sector innovations is reported in Mansfield et al. (1977).

In that context, the results reported here (in terms of Industry Rate of Return) are close to the middle of the range for rates of return on other innovative activities undertaken by industry; however, observe that the nanotechnology standards development investments examined in this report are very different from the collection of innovative investment projects examined by Mansfield et al. The nanotechnology standards investments are investments in infrastructure technology that, because of their intrinsic "public goods" content, are especially likely to have large industry-wide social benefits for the reasons discussed earlier in this paper. The evaluation metrics reported here for the nanotechnology standards development investments are also within the range of the evaluation metrics for many other public–private partnerships to develop infrastructure technologies that have been evaluated by NIST over the last 20 years (Link and Scott 1998, 2012, 2013).

4 The perspective of universities

Clearly the nanotechnology documentary standards are important for industry, but our discussions with researchers in universities reveal that the standards are not considered important in the work of many university-based developers of nanoscience and nascent nanotechnology. There were only the five completed responses from universities about the five most important standards, and those few were already committed to the standards development process.

Several non-responses from universities were accompanied by email exchanges, the crux of which was that many university-based researchers do not appreciate the utility of standards because the academic community, as such, incentivizes scientific innovation rather than standardization. According to one member of the university community, reflecting the sentiments expressed in fewer words by many others:

> Academic research is based upon peer-reviewed scholarly literature. Information about pre-existing methods is drawn from the "materials and methods" section of published papers. Definitions of terms are based on who coined the phrase, or how the term is widely used, in the literature. Standards documents, whether they agree or disagree, carry little to no weight, and I think that most academic researchers have little awareness of them.

To some extent, too, university researchers are just focused on other issues. According to a university researcher and SDO participant:

> [A]cademics have a different perspective on standards development since they can investigate libraries of ENMs [engineered nanomaterials] that may not be of immediate interest to industry or suitable for certification as reference materials." (Hackley et al. 2009)

Some university non-respondents are simply unaware of standards or their relevance to their operations. One nanofabrication center manager felt he had no contribution to make, saying:

> I manage a purely research-oriented university lab, and don't have any knowledge of these standards. My input would not be useful.
> I would be very surprised if our grad student researchers were aware of the standards. [...] I can't say how much our site director knows about the standards since I can't recall discussing them with him.

Following-up with the site director, the manager's expectations were confirmed:

I am not familiar with the standard development process, and I could only guess as to their utility to industry. I would think that you would be better served by contacting people in industry or in trade groups that serve industry in the nano sector.

In the light of the value chain discussed in Sect. 1 and the economic policy assumption that it is desirable for university research to develop knowledge that is useful for industry innovation, the distance from the university focus to an industry focus regarding nanotechnology standards is too great. Another thoughtful non-respondent focused on some of the university's more immediate links to industry, saying:

While I can imagine that some of the equipment we use is subject to some of the standards in [the survey] Appendix, it would be the vendors who would relate to them better than our students. …[Y]ou're right from the instrumentation calibration perspective, [but] we rarely do our own. We send them to the vendors. My thinking is that unless a research topic specifically required us to read/review specific standards they would not be looked at. Times have certainly changed – I recall as an undergraduate back in the late 70's - it [discussion of standards] was almost a daily staple for some of the classes I was taking. … Looking at some of the titles under ISO, they would be highly useful. I know as a unit and institution we're becoming more aware of the safety (EHS) aspects of nanotechnologies. [Regarding] university … start-ups, good question. I know our tech transfer folks are very interested in licensing IP (university patents) [but] where the standards come into play … I'm not sure – though – certainly if it goes to manufacture [there should be a connection].

Currently, the links from industry standards to the university community are not obvious. An engineering professor and SDO participant observes:

The College and University are developing nanotechnology IP and licensing it, but there are few links between this and the ISO, ASTM, IEC standards developed so far.

Others appear to believe that the impetus for the linkage between standards-related activities and the universities is most likely to come from the outside, as one respondent said:

The drive to establish this suite of methods is driven by the board… consisting of representatives from industry, national labs, and other educational institutions.

While survey participation was limited, participants' formal and informal responses and communications provided a wealth of information and insights about early stage development of nanotechnology standards. One of these insights is that there appears to be a lack of extensive linkages in the value chain connecting universities, increasingly anxious to transfer their technology, to the industry-wide perspectives represented by SDOs. The SDOs studied here appear to be populated by future-focused industry representatives struggling to lay the technical infrastructure intended to clear some paths to nanotechnology commercialization.

Even for the universities that reported the five nanotechnology standards most important for their work, there was a statistically significant difference accorded to the importance of standards other than those about vocabulary, terminology, or classification and those about health and safety. Nanotechnology standards of those types were valued by both universities and the industrial respondents. But, the industrial respondents were statistically much more likely also to consider material specification and characterization standards to be important for their work.

To quantify the difference between the university and industrial respondents regarding the importance of materials specification and characterization nanotechnology standards for their work, the forty standards were divided into three categories: (1) vocabulary, terminology, or classification system, (2) health and safety, and (3) materials specification and characterization not obviously in the health & safety category. With the 40 standards divided into the three broad types, there are 9 in the vocabulary, terminology, or classification category, 9 in the health and safety category, and 22 in the materials specification and characterization category.

A purely randomly selected standard has a probability of 9/40 of falling into the first category, a probability of 9/40 of falling into the second, and a probability of 22/40 of falling into the third.[17] The random variable x_i that has value 1 if a standard falls into the third category and zero otherwise has an expected value of $22/40 = 0.55$. Its variance σ_i^2 is $((0 - (22/40))^2(9/40)) + ((0 - (22/40))^2(9/40)) + ((1 - (22/40))^2(22/40)) = 0.2475$, and the standard deviation is 0.4975. Against the null hypothesis that university respondents chose the standards randomly, the sum of m such random variables has expected value m times 0.55, with variance m times 0.2475.

Each of the five university respondents provided a list of the five nanotechnology standards of most importance to the university. If those standards had been purely randomly selected, the expected value for the number of the five standards that would have fallen into the category for materials specification and characterization would be the expected value of the sum from 1 to 5 of the identical random variable with the expected value of $22/40 = 0.55$ and variance $= 0.2475$. Thus, the sum has the expected value of 2.75 (the product of 5 and 0.55) with variance of 1.2375 (the product of 5 and .2475). The sum of the five random variables has a standard deviation equal to 1.11 (the square root of 1.2375). Of the five university respondents, four are large, major U.S. universities. For all four, among the five most important nanotechnology standards for the university, none were in the category for materials specification and characterization. Thus, for each of the four responding U.S. universities, the number of standards in the third category was significantly less than expected—2.48 (equal to 2.75/1.11) standard deviations below the number expected against the null hypothesis of a random choice of standards.[18] The one university respondent from outside the U.S. was an exception. It had three of its five most important standards in the materials specification and characterization category—insignificantly different from the expected number against the null hypothesis.[19]

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[17] There are then three "boxes" into which a chosen standard can fall with probabilities 9/40, 9/40, and 22/40. The approach to evaluating the statistical significance of the difference between universities and industry in the types of standards of most importance to them is an application of the approach used in Scott (1993, pp. 124–128). It is a conservative approach that does not depend on the properties of large-sample estimators or normality.

[18] For a readily seen upper bound on the p value, from Chebyshev's inequality, the probability of such a large deviation is less than the reciprocal of that squared deviation, or <0.163.

[19] Alternatively, we could think in terms of the average outcome for the U.S. universities. An average $X = (1/m) \sum_1^m x_i$ for a sample of m of the random variables has expected value $E(X) = (1/m) \sum_1^m E(x_i) = 0.55$. Given the null hypothesis of pure randomness, the variance of the average is the double sum over the weighted terms in the covariance matrix for the m random variables, and given the assumption of pure randomness, that double sum is $(1/m^2) \sum_1^m \sigma_i^2 = (1/m)\sigma_i^2 = (1/m)(0.2475)$. Against the null hypothesis, the expected average outcome for the four U.S. universities would be 0.55 with standard deviation equal to 0.25 (the square root of one-fourth of 0.2475). The average outcome for the U.S. respondents is then 2.2

Eighty percent of the responding universities, and 100 % of the responding U.S. universities, showed a statistically significant absence of the importance for their work of the standards in the materials specification and characterization category. In contrast only 50 % of the 12 industrial respondents answering the question reported a statistically significant shortfall in the expected number of important standards in that category. For half of the industrial respondents, the number of materials specification and characterization standards were not significantly less than expected against the null hypothesis, and in three of those six cases, the number exceeded the expected value.

5 Conclusion

The National Nanotechnology Initiative in the United States has made the development of nanotechnology a high-priority, publicly-funded science and technology initiative (Bozeman et al. 2008). The research of Bozeman et al. (2008) identified key barriers to the diffusion of nanotechnology to be the lack of access to early stage venture capital and to university equipment and facilities. To address those barriers, they recommended that states assist nanotechnology firms with venture capital and that states provide universities with incentives to share their equipment and facilities with nanotechnology firms. This paper's evaluation pointed to two barriers in the development of documentary standards to support the commercialization of nanotechnology, and we conclude by juxtaposing those two barriers with recommendations for policy to mitigate them.

First, many firms that are commercializing nanotechnologies are free-riding on the documentary-standards investment efforts of other firms. The free-riding is expected to suppress investment in the standards development process below the social optimum, because the firms incurring the costs of the process appropriate only a small portion of the social benefits created by their investments. In that view, free riders are a symptom and a cause of the appropriability problem. They are a symptom in the sense that they have opted to free ride, rather than invest in standards development, because they cannot appropriate the returns of their investments. They are a cause in the sense that the appropriability problem occurs because they appropriate benefits created by the investments of others.[20] Public policy can address the appropriability problem by providing more support for standards development with public funding to subsidize the efforts of firms. Such public funding can increase the expected private rate of return above the hurdle rate for a firm participating in standards development.[21] In addition to funding that directly subsidizes the investments of firms in the standards development process, public support for the participation of public laboratories such as the National Institute of Standards and Technology (NIST) provides support that will increase the efficiency of the standards development process.[22]

Footnote 19 continued
standard deviations below its expected value. For the readily computed upper bound p value, from Chebyshev's inequality, the probability of such a large deviation is less than the reciprocal of that squared deviation, or <0.21.

[20] However, we have observed that the forward-looking SDO participants are appropriating substantial returns from their investment; moreover, they may do even better in the future because of their early involvement in the development of documentary standards.

[21] See Link and Scott (2011, pp. 5–8, pp. 119–123).

[22] See Leyden and Link (1999).

Second, many university researchers who are developing the science behind nanotechnology, and whose universities would like to see the scientific knowledge successfully transferred to commercial applications, are completely isolated from and unaware of the documentary standards being developed in industry that will be needed for successful transfer of university knowledge to industrial applications. To increase university researchers' awareness of industrial documentary standards and the usefulness of both the university research and the documentary standards for the successful transfer of scientific knowledge to industry and the commercialization of nanotechnologies, federal grants for university research about nanotechnology could require, as a part of the research protocols, interactions with industry's standard setting organizations.

The qualitative assessment presented here indicates that SDO participants are very future-focused and relatively well situated to reap the rewards of the burgeoning growth in nanotechnology-based products and services markets. The large net benefits shown in Table 7 that accrued to the non-participant free riders are because they did not incur the costs of participating in the SDO nanotechnology standard-setting activities, yet they received the benefits net of only their pull costs. The record of benefits and costs for the free riders exemplifies the positive externality created by the nanotechnology standards setting activities of the SDO participants. Another finding is that the universities that develop knowledge about nanoscience with the potential to be transferred to industry in the form of commercialized nanotechnology often do not perceive that the nanotechnology documentary standards are important for their work and largely ignore the standards. Even those universities that do recognize the importance of the nanotechnology documentary standards for their work often do not find the materials specification and characterization standards as significant as do the industry respondents as a group. The asymmetry in the views of universities and industry about the importance and use of nanotechnology documentary standards may inhibit the transfer of nanoscience and nanotechnology into commercialized products and services.

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