Forecasting Innovation Pathways: The Case of Nano-enhanced Solar Cells

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ABSTRACT

We have recently devised a 10-step framework to extend research profiling to help identify promising commercialization routes for a target emerging technology. Our approach combines empirical and expert analyses. We herein illustrate this framework for the case of nano-enhanced solar cells.

INTRODUCTION

Our endeavors should be considered within the context of Future-oriented Technology Analyses ("FTA" – see http://foresight.jrc.ec.europa.eu/). Over the years, FTA tools have expanded from technology forecasting of incrementally advancing technologies (for example, consider Moore's Law describing some six decades of continual advances in semi-conductor capabilities).[1] Today, considerable interest is directed toward New & Emerging Science & Technologies ("NESTs") as increasingly, NESTs are anticipated to provide considerable wealth creation. These forms of technologies tend to be less predictable than incremental innovation processes; they are more dependent on discontinuous advances; and the anticipated (disruptive) impacts on markets and on society are difficult (although not impossible) to foresee. In our endeavor to grapple with this challenging situation, we seek to provide usable intelligence, not only to get a handle of the discontinuous development of NEST's, but also on the pertinent contextual forces and factors affecting possible technological innovation. However, technology opportunities analysis[2] for NESTs poses notable challenges.

Recently, we put forward our approach to Forecasting Innovation Pathways ("FIP").[3] That paper provides conceptual background for our endeavors to combine "Tech Mining"[4] and "Multi-path mapping."[5] It explores the promise of this approach through its application to two illustrative innovation situations, for nano-biosensors and for deep brain stimulation. This paper illustrates application of the FIP approach for a further case, that of nanotechnology-enhanced solar cells ("NESCs"). In particular, we focus on a specific type of solar cell, Dye Sensitized Solar Cells ("DSSCs").

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THE FIP FRAMEWORK

The FIP framework includes four stages:
Stage 1 – Understand the NEST and its critical environment
Stage 2 – Tech Mine
Stage 3 – Forecast likely innovation paths
Stage 4 – Synthesize and report

Figure 1. Framework to Forecast NEST Innovation Pathways

1. Understand the NEST and its TDS (Technology Delivery System)	Step A: Characterize the technology's nature
	Step B: Model the TDS
2. Tech Mine	Step C: Profile R&D
	Step D: Profile innovation actors & activities
	Step E: Determine potential applications
	Step J: Engage experts
3. Forecast likely innovation paths	Step F: Lay out alternative innovation pathways
	Step G: Explore innovation components
	Step H: Perform Technology Assessment
4. Synthesize & report	Step I: Synthesize and Report

To operationalize these stages, we break them down into 10 steps (Figure 1). We label these "A through J" but should emphasize that forecasting innovation pathways is not a once-through, linear process. Rather, it is one that gathers information pursuant to the various steps, being quite willing to revisit earlier steps as one learns more about the emerging technology and distinguishes vital issues affecting potential commercial or other applications. In particular, we have set "Step J" – engage experts – deliberately out of sequence to call attention to it. In our FIP exercises to date, expert engagement has tended toward informal, in-depth involvement of a limited number of knowledgeable individuals. We distinguish that from formalized involvement of many experts (e.g., Delphi procedures), although one could consider augmenting the FIP approach by such techniques.[v]

Stage 1 is targeted to get the first understanding of the technology – how it works and what functions it can accomplish (Step A). In addition, we work to characterize the organizational and contextual factors involved in developing and applying this technology (Step B). We have adopted one of many innovation systems modeling approaches,[6] some addressing NESTs[7] -- the Technology Delivery System ("**TDS**") approach[8, 1] -- to reflect contextual dynamics. We find it suitable for FIP by distinguishing: 1) the enterprise to translate R&D findings to a bonafide innovation and take that to market, and 2) the key contextual factors affecting the success of that innovation process. Stage 1 is largely descriptive.

Stage 2, in contrast, is heavily empirical. We search for R&D activity in suitable Science, Technology & Innovation ("ST&I") databases, and profile that activity and the associated actors from these data (Steps C & D). There are many analytical tools to help profile R&D, including bibliometric analyses, social network analyses, and trend analyses. We adapt these to facilitate our study as a function of the NEST's state of development. We seek innovation indicators (i.e., the

[v] The FIP framework is designed to put tools to work in a systematic way, and should be taken as a menu that can be tailored and added to, although we argue that the stages and steps can be generalizable.

empirical measures to help gauge technological maturation and prospects for successful applications[4]). We also seek to figure out how technological characteristics link to functional advantages, applications, and potential users (Step E).

As mentioned, Step J, "engage experts," is an iterative and ongoing process. This depends on the Competitive Technical Intelligence ("CTI") analysts' knowledge of the target technology. In our case for nano-enhanced solar cells, we only claim modest knowledge, so we needed guidance throughout the process. At Georgia Tech, we drew upon a couple of faculty members to orient our work. Most importantly, we found a willing PhD student (Chen Xu) to collaborate in our analyses. Later, we gathered approximately ten persons knowledgeable about the technology and policy aspects for an afternoon workshop. In other cases, the CTI team may include persons deeply conversant with the target technology, altering the nature of expert inputs needed. Such expert interactions are best if ongoing and iterative. For instance, early formulation of the TDS with pointers toward key institutions may illuminate needs for special expertise. Eliciting advice from such experts may, then, lead to identification of additional (or different) key players in the TDS, and so forth.

Stage 3 brings expertise to bear on the empirical results. Step F digests the prior results to present those to participating experts and stakeholders. Convening a workshop with multiple perspectives can anchor Step G explorations of alternative innovation pathways. This is meant to be a creative endeavor to identify potential applications and array different ways to attain these. It should take into account competing technologies that could hold advantages over the target NEST under study. After a stage of open brainstorming workshop activities, it is desirable to elicit ideas from the experts on "issues." That is, what are important hurdles to be surmounted along the various innovation pathways? What are key policy and/or business management leverage points to enhance the prospects of success? If possible, it can also be valuable to obtain the views of the participants on impact assessment – i.e., what are potential "unintended, indirect, and delayed" effects[9] that could arise from pursuing a given development path?

Stage 4 (Step I) consists of integration and communication. The aim is to synthesize what has been revealed about alternative innovation pathways for the NEST under study. Multiple modes (including interactive means) should be considered to communicate findings to various target users. As suitable, additional diagnoses based on the findings could lead to targeted recommendations (e.g., what steps should our organization pursue regarding development of this NEST?).

THE CASE OF NANOTECHNOLOGY-ENHANCED SOLAR CELLS (NESCS)

Stage 1. Understand the NEST and its TDS (Technology Delivery System)

We offer a number of analytical examples pertaining to NESCs. We present these as a vignette, not a full-blown case analysis. The motivation for the analyses is scholarly inquiry, not real-time CTI.

Step A calls on the analysts to characterize the technology. Elsewhere, we have explored NESCs and DSSCs in more detail.[10] [11] [12] Here we note the importance of understanding how these solar cells work, what functions are important on the R&D agenda, and how the technology could be applied.

Society's energy needs promote special interest in renewable energy sources, such as solar cells. Solar cells can be characterized in three developmental generations.[13] First Generation-- "Conventional Solar Cells," made from crystalline silicon, account for ~90% of the market, but these are expensive. Second Generation ("Thin-film Solar Cells)" can be divided into two groups: "Silicon Thin-film" and "Compound Semiconductor Thin-film." The latter employ nanotechnology to improve efficiency -- e.g., enlarge the effective optical path for absorption by using nano-materials. Third Generation solar cells or "New Concepts Solar Cells" are classified in different ways. We note two groups: 1)

"Compound Semiconductor Thin-film Solar Cells" that employ quantum dots to enhance efficiency, and 2) "Dye-sensitized Solar cells."[14] These DSSCs also apply nanotechnologies to enhance cell performance.

Step B calls for modeling the Technology Delivery System ("TDS"). We emphasize two perspectives in addressing such socio-economic systems:

a) Push-Pull Enterprise Analysis – to capture the key entity or entities (organizations) to take the emerging R&D advances (the "Push") and connect those to potential users – i.e., markets (the "Pull")
b) Contextual Forces Analysis – to identify the key factors that will promote, or impede, the intended technological innovation (typically, oriented toward product or process commercialization).

Figure 2, below, offers a high-level TDS for DSSCs.[15] Based on our analyses of current developments and target applications, we think it important to track the involvement of three sorts of companies – those pursuing research; those emphasizing development (in the form of patenting); and those associated with identifiable business initiatives. We find relatively few companies doing all three. Later, we will illustrate further probing into the key DSSC actors.

Figure 2 also shows notable governmental and competitive factors. The recent upsurge in support for renewable energy promotes solar cell initiatives. Long term, we believe general economic forces will likely be conducive to innovation, but the short term global economic malaise has hit the solar cell market hard. DSSCs currently hold a minuscule share of the market, but hold bright prospects. This TDS provides a framework to share with experts to advance more in-depth deliberations.

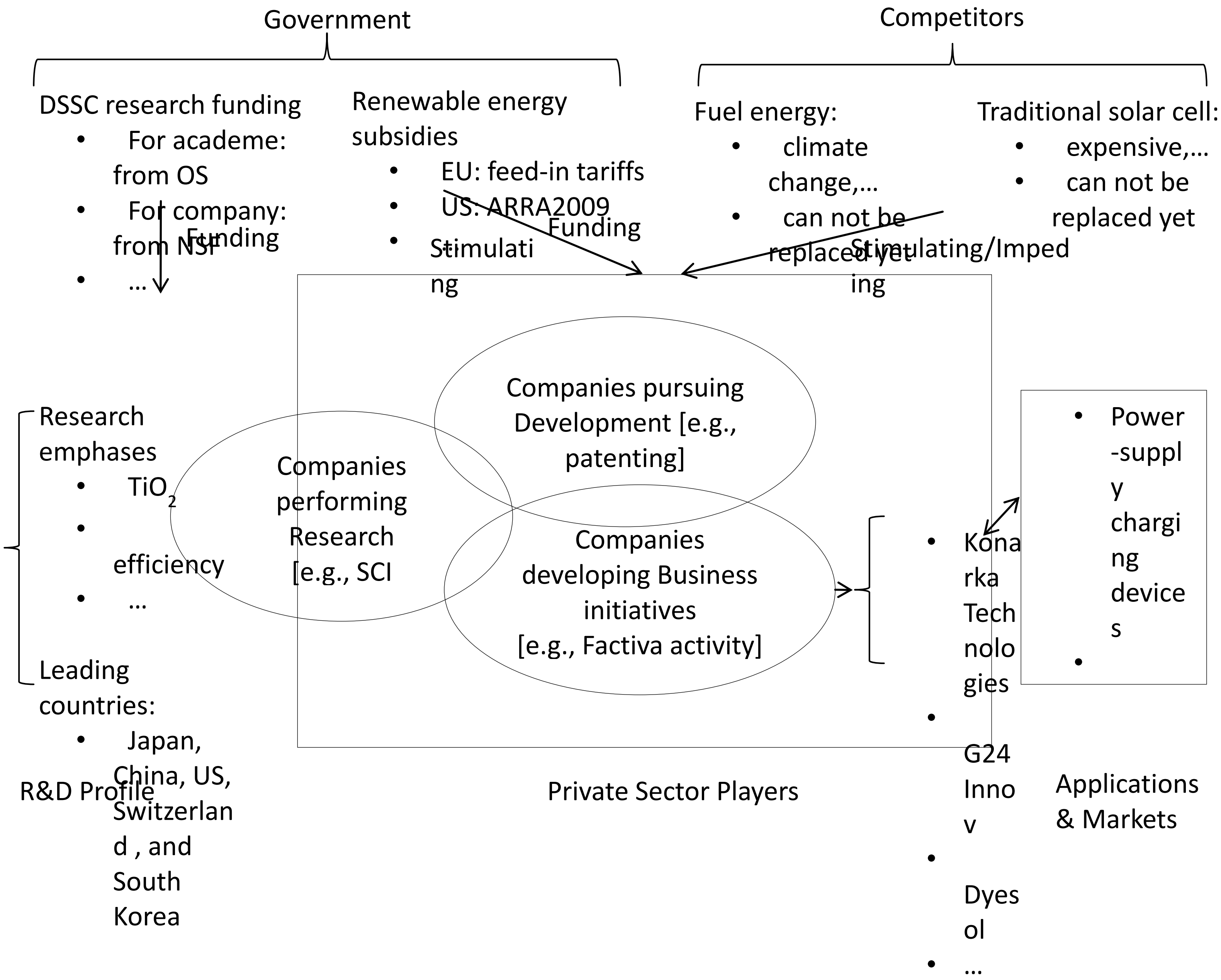
Stage 2. Tech Mine

Stage 2 leads us into three empirical elements of FIP. These build upon database searches to retrieve information on R&D, patent, and business-related activity concerning the technology in question. In addition, in our Framework (Figure 1) we situate Step J, Engage Experts, here. However, as noted, this is just to ensure that we don't neglect to involve experts throughout the study, as needed and where feasible. To conduct Stage 2 well, one truly needs to integrate empirical and expert information.

Step C involves detailed R&D profiling work. With respect to DSSCs, we searched and downloaded abstract records from four databases. After cleaning, we have:

- 2168 publications from the Science Citation Index (SCI), reflecting fundamental research from the seminal O'Regan and Gratzel paper [14](in 1991 through 2009
- 2593 publications from EI Compendex, reflecting more applied (engineering-oriented) research from 1991 through 2009
- 1559 patents from the Derwent World Patent Index (DWPI)
- 1372 records from the Factiva database, capturing business-related activity (e.g., press releases, trade publication coverage), from 1997 through 2009.

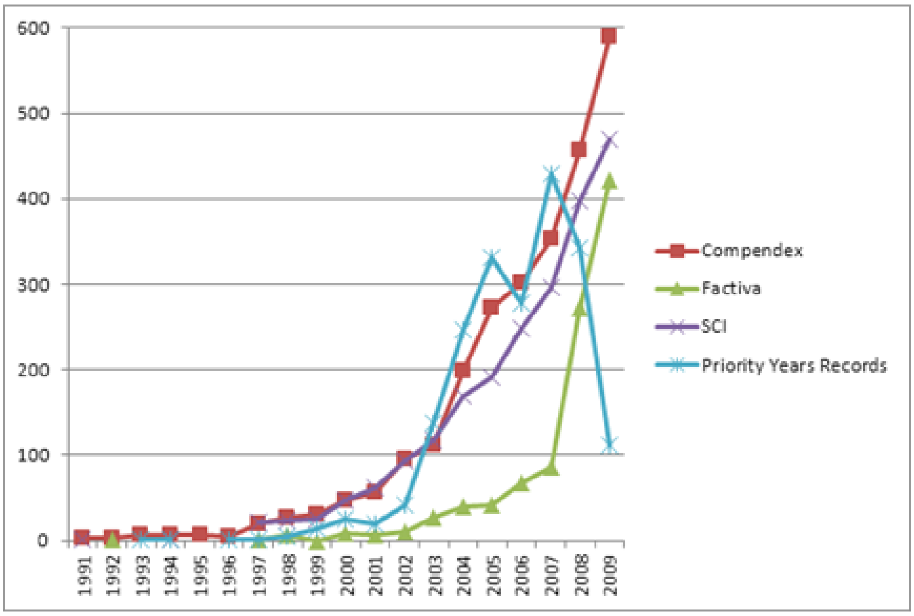
Figure 2: Technology Delivery System for DSSCs


Government
Competitors
DSSC research funding
For academe: from OS
For company: from NSF
…
Funding
Renewable energy subsidies
EU: feed-in tariffs
US: ARRA2009
…
Stimulating
Funding
Fuel energy:
climate change,…
can not be replaced yet
Traditional solar cell:
expensive,…
can not be replaced yet
Stimulating/Impeding
Research emphases
TiO_2
efficiency
…
Leading countries:
Japan, China, US, Switzerland , and South Korea
R&D Profile
Companies performing Research [e.g., SCI
Companies pursuing Development [e.g., patenting]
Companies developing Business initiatives [e.g., Factiva activity]
Private Sector Players
Konarka Technologies
G24 Innov
Dyesol
…
Power-supply charging devices
Applications & Markets

We draw upon these data, together with additional internet probes and expert advice, to work on all three Stage 2 steps. Concerning R&D, we are especially interested in learning about technological maturation and "hot" topics, key organizations, and networking among the R&D players at country and organization level. We selectively illustrate here to give the flavor of FIP-oriented "Tech Mining" [4]. Figure 3 compares activity trends from the four database searches. Some points of note:

- Note the tremendous growth rate in activity in all four sources
- Concerning R&D, it is interesting to see that scientific research (SCI) has risen together with engineering-oriented research (Compendex), and with patenting [the recent drop in patent priority year numbers is an artifact of patent family data]
- Note the upsurge in publication and patent activity around 2003, and the subsequent burst in commercial activity from 2008 – suggesting that this technology could well be on the brink of major commercialization.

Figure 3. Dye Sensitized Solar Cell Trend Analyses



We applied science overlay mapping[16] to locate DSSC R&D among the disciplines. This approach uses the Subject Categories that Web of Science assigns to journals. So, for a set of publications indexed by Web of Science (in this case, by SCI, which is part of Web of Science), we locate this research via the journals in which it appears. Figure 4 overlays DSSC research over a base map reflecting the 221 Subject Categories shown by the background intersecting arcs. The Subject Categories are grouped into "macro-disciplines" based on the degree of co-citation of the Subject Categories in a large sample of articles indexed by Web of Science.[17] Those macro-disciplines become the labels in the figure. The DSSC research concentrations appear as nodes in the map, with larger nodes reflecting greater numbers of publications.

Figure 4 illustrates that global DSSC research involves an extensive range of research fields concentrated in the Materials Science and Chemistry macro-disciplines. This analysis helps understand the fields involved, to help identify technical experts.

Figure 4. DSSC Science Overlay Map

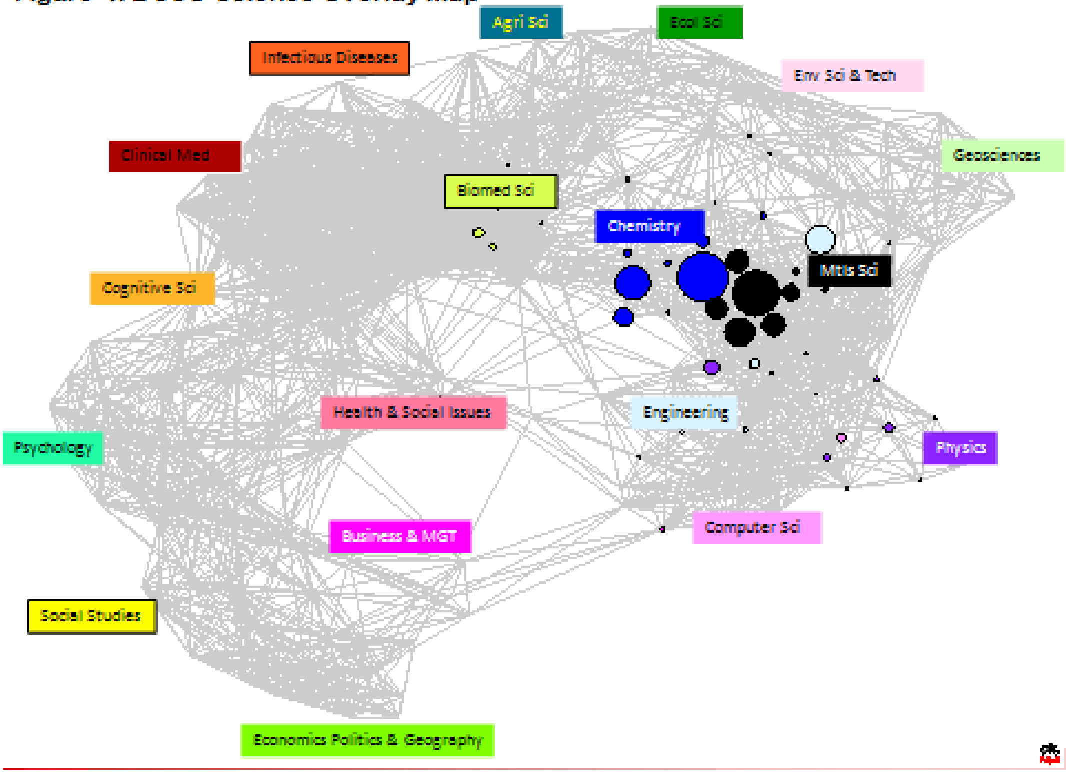


Figure 5. Geo-map of DSSC Research Organizations in China (based on SCI)

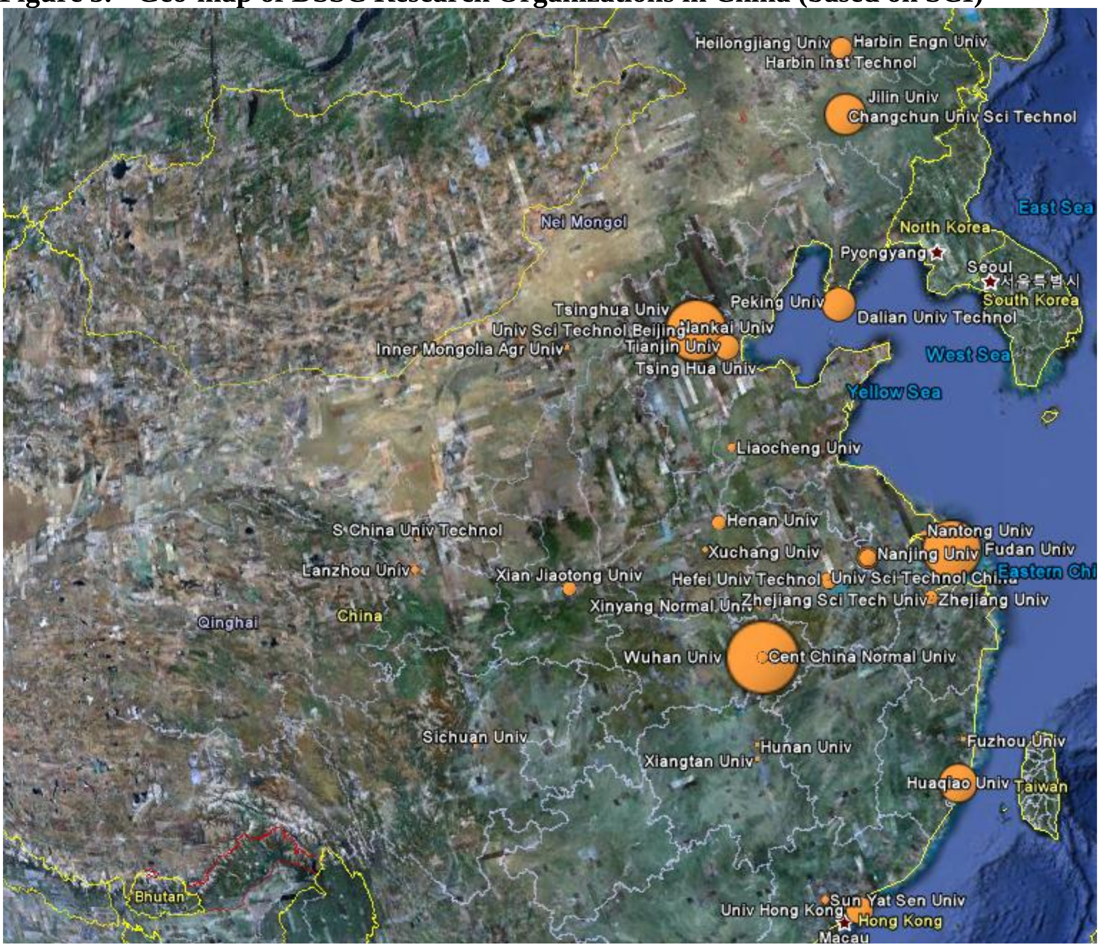
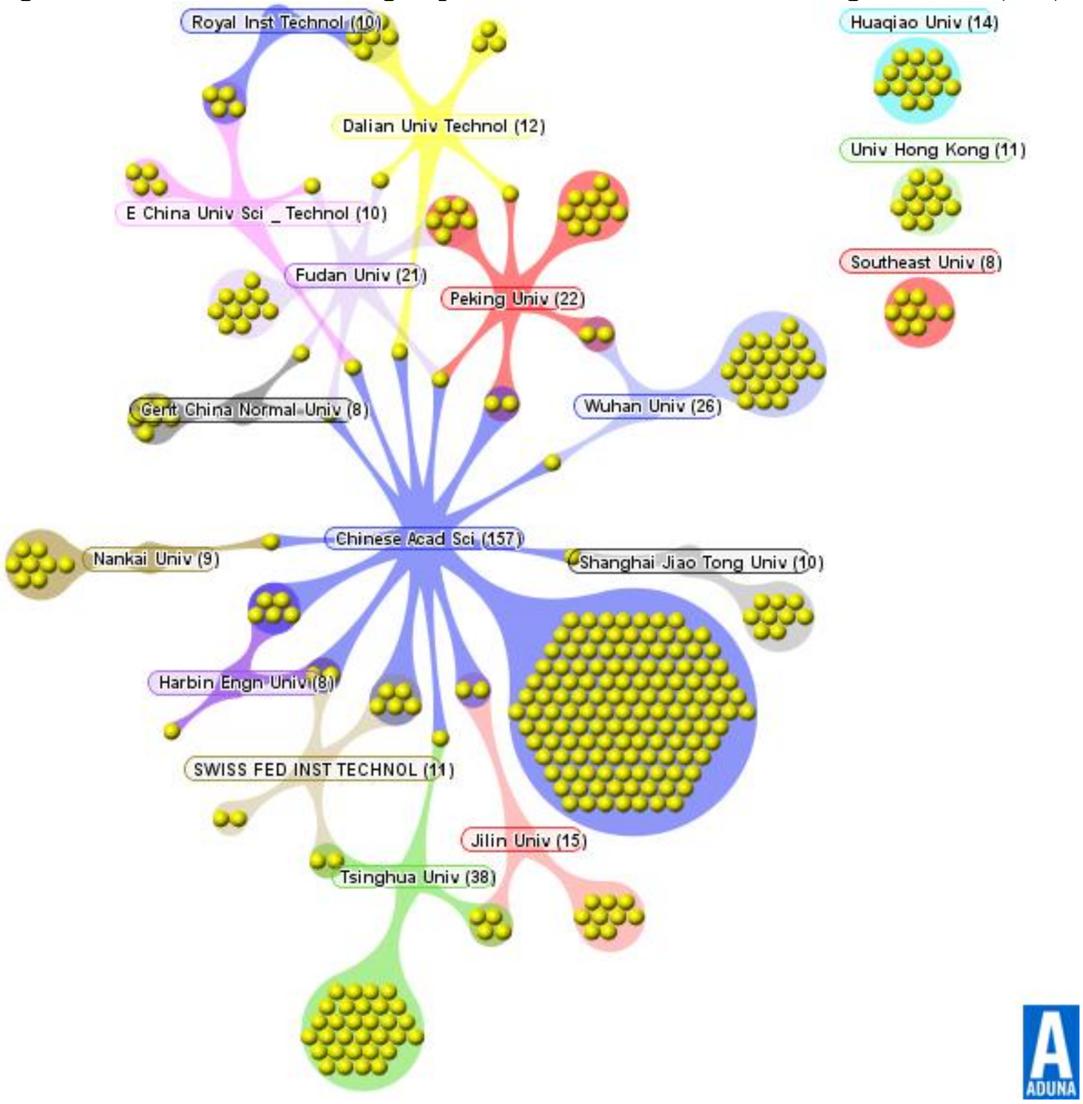


Figure 5, above, locates Chinese research organizations with many SCI publications on DSSCs. The leading organization, the Chinese Academy of Sciences (with 156 of 413 publications located) is not shown. Such geo-mapping supports analyses of regional concentration and location of research "hotbeds." [The map is made using a VantagePoint (closely related to Thomson Data Analyzer (TDA)) software macro together with Google Earth.]

Figure 6 shows social networking among these leading DSSC fundamental research organizations. In this case, the Chinese Academy of Sciences is included (with all its institutions collapsed together). In Thomson Data Analyzer, one could click on a given paper or set of them to examine the authors, topics, etc. In this way the analyst can identify relationships among key institutions. Interestingly, some of the highly collaborative institutions are not themselves in China – e.g., Royal Institute of Technology and the Swiss Federal Institute of Technology. They collaborate on sufficient papers with Chinese colleagues to appear here.

Figure 6. Collaboration among Top 15 Chinese DSSC Research Organizations (SCI)



Step D is to Profile Innovation Actors & Activities. The dividing line between Steps C and D is not distinct. Indeed, the results just described help us move forward with Step D objectives. A particularly useful empirical approach here is to identify the leading organizations active in each of the different data sources. Table 1 compares selected organizations in this way. Note the variation in prominence across these datasets. For instance, Samsung is the leading patenter and publisher (in this compilation) on DSSCs, but has not been frequently mentioned in conjunction with business actions (Factiva). Dainippon Printing is extremely active in patent families, but does not publish. The use of multiple information sources in conjunction with each other enriches the CTI perspective.

Table 1. Cross-Data Analyses: Leading "Actors"

Selected "Players"	SCI	Compendex	DWPI	Factiva
Samsung	28*	29*	54*	1
Nippon Oil Corp	14*	25*	25*	7
Sharp Co	12*	21*	35	2
FUJIKURA LTD	4	6	40	13*
KONARKA Technologies	4	8*	15	12*
Sony Corporation	6	10*	42	7*
DAINIPPON PRINTING CO LTD	0	0	52*	3
Hahn Meitner Inst Berlin GmbH	21*	0	0	0

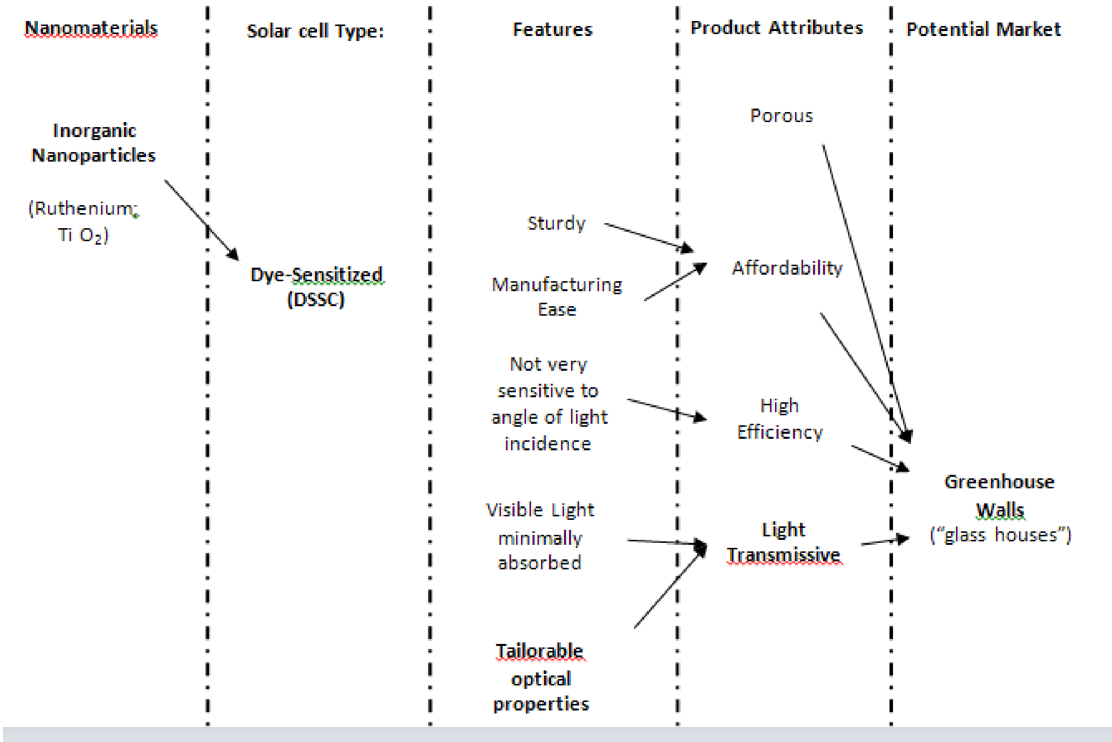
An especially useful analytical step, once such highly active players have been identified, is to profile their R&D and business activity in detail. Using software aids, such as Thomson Data Analyzer and MS Excel, one can generate "breakout tables" quickly. Depending on one's CTI foci, these might detail for, say, the leading patent assignee companies:

- Their country
- Most active International Patent Classes
- % of their patents in the most recent years
- Leading inventor teams
- Any notable collaborators

Step E. is to Determine Potential Applications. We have introduced a new technique called "cross-charting" to explore the links from technological attributes (e.g., particular nanomaterials or nanostructures; particular technical advances) -- to functional advantages that those offer – to potential applications – in particular markets. The content of a given cross-chart will vary depending on the CTI interests at hand. For DSSCs, we began by generating an overall cross-chart, seeking to understand whether most technical gains would point to highly specific functions and applications, or would instead be generally advantageous. The resulting "spaghetti" chart (not shown here) suggested that most nano-enhancements were potentially quite general, contributing to a wide range of possible uses.

Figure 7 presents a follow-on cross-chart. Here we have imagined that our CTI effort focuses on a particular target market – greenhouses (or other glass-walled building structures). We work our way back from that intended innovation to identify particular attributes that could contribute importantly to it (e.g., light transmitting solar cells). We continue *upstream* to direct attention to features, solar cell types, and advantageous nanomaterials. The idea is that this would help us focus ongoing monitoring efforts to seek out advances that could help us achieve our desired application. Conversely, we would direct less attention to other nanomaterials and solar cell types.

Figure 7: Focused DSSC Cross-Charting:
Tracking Materials to Technology to Functions to Applications



The cross-chart could spawn related probes. For instance, we could search within our patent set to see which assignees appear to be the most involved. Searching claims and uses fields within DWPI reveal some 19 patent families, of which Samsung holds 6. That suggests that it may be worthwhile to look within Samsung patenting. We find a total of 54 DSSC-related patent families. Mapping inventor collaboration patterns suggests two relatively separate R&D teams, one of which is associated with all of the glass-wall patents. Next steps might include visiting Samsung websites and direct discussion with their inventors.

Alternatively, other cross-chart foci are quite possible. Were our interests centered on a given technical aspect (e.g., cheaper film deposition methods), we could make a different cross-chart to accentuate relationships with that capability. This could help identify potential partners with complementary interests at different places along this technology development progression, thereby serving "Open Innovation" purposes.[18]

Stage 3. Forecast Likely Innovation Paths

Step F lays out alternative innovation pathways. This stage was conducted in two rounds. The first round involved face-to-face interviews with researchers at Georgia Institute of Technology (US), which provided input to allow a first evaluation of our analyses. The second round entailed a campus workshop (~10 participants including ~5 with particular knowledge in nano-enhanced solar cells). This focused on mapping likely innovation avenues, following the process described and demonstrated by Robinson and Propp.[5] Their expert workshops involve a wider spectrum of experts and stakeholders for a more extended interaction (e.g., full day). We then called upon our collaborating expert, Chen Xu, again to help interpret results from the workshop (lots of notes).

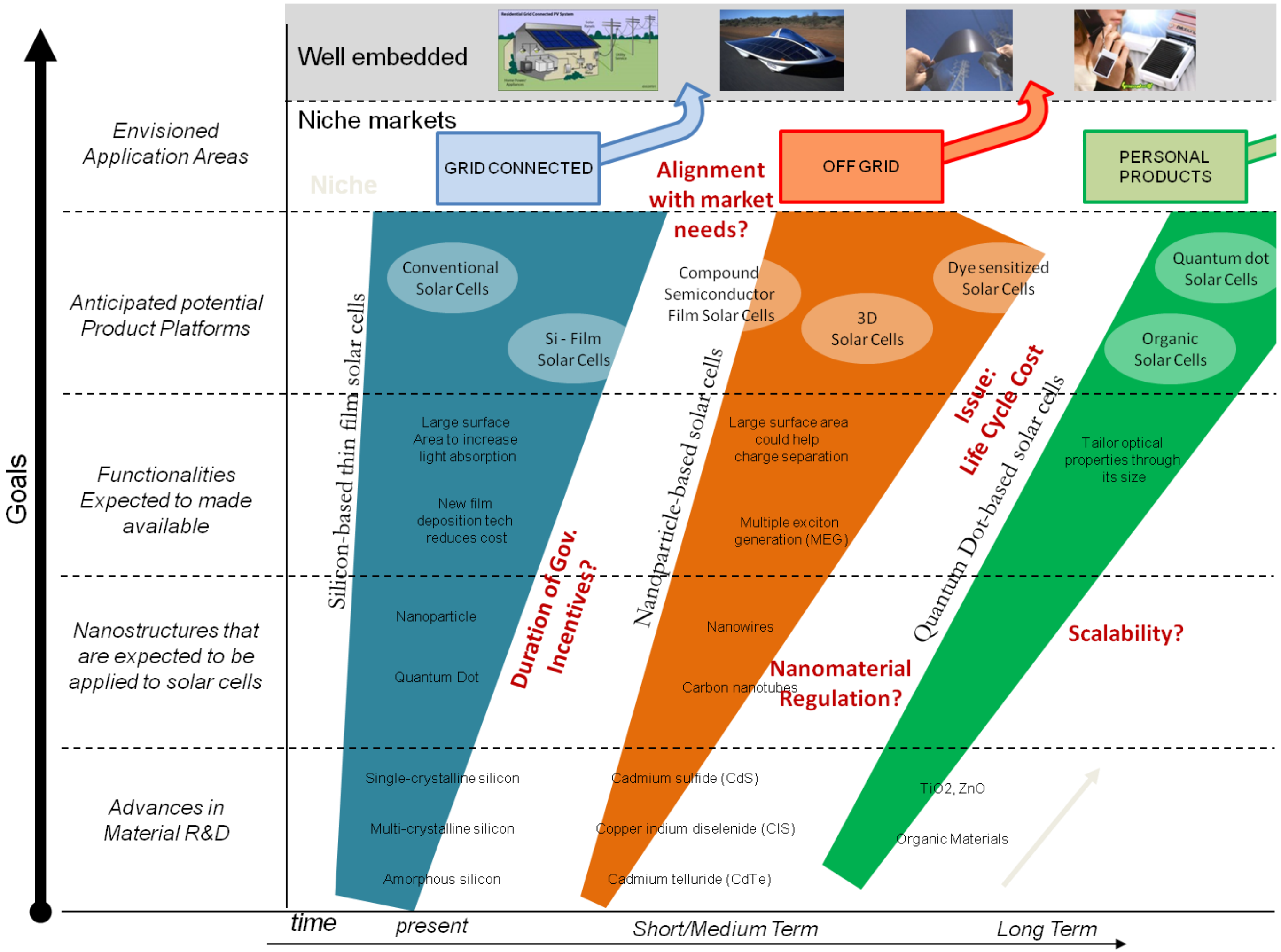
Figure 8 shows the baseline slide to initiate the process. It presents some key elements that we found from our interviews and desk research and is presented in a way to locate elements that would add value to the solar cell innovation chain (the y-axis), and position them (x-axis) in a timeline to show how we positioned the expectations of when these elements would become reality. This provides a framework for discussion and rapid feedback. Such visualizations are essential in workshop interactions where time is limited, but also to create a framework for drawing out the intelligence held by the experts in the workshop, a scaffold to locate knowledge.

From such discussions, you can reshape the framework and cluster potential innovation pathways, identify the key promising technologies, position them in a time frame and locate obstacles, barriers and opportunities that will facilitate or inhibit progress along a particular pathway. Once complete, such a multi-path-map can be updated, monitored and circulated to the experts in the workshpop (and others) for verification and expansion. A centerpiece to exploring innovation avenues for potentially disruptive NEST, where the future is open-ended and thus an evolving map is needed. Figure 9 gives a simplified example of a multi-path-map for solar cells.

Figure 8. Populating the multi-path framework

	Present	Short/medium term	Long term
Application area	▪ Grid connected	▪ Off-grid ▪ Personal Product	
Product	▪ Silicon Thin-film Solar Cell ▪ Compound Semiconductor Thin-film Solar Cells	▪ 3 D solar cells	▪ Dye-sensitized solar cells ▪ Organi
Structure function	▪ Large surface area could increase light absorption ▪ Provide new film deposition methods to reduce cost	▪ Large surface area could help charge separation ▪ Multiple excition generation (MEG)	▪ Tailor optical properties through its size
Nanostructure	▪ Nanoparticle Quantum dotTraditional	Nanowires Fuel Carbon nanotubesPrivate	
Material	amorphous ▪ TiO2, ZnO…… ▪ Organic materials	cadmium sulfide (CdS)Government copper indium diselenide (CIS)Renewable energy subsidies cadmium telluride (CdTe)DSSC	

Figure 9. Multi-Path Map for Dye Sensitized Solar Cells



You can identify lead and lag relationships from silicon-based -- through quantum dot enhanced -- solar cells. It suggests that the latter may point toward more niche-market, special application (higher price) applications. The silicon lead could prove tough competition for those pursuing such applications (much as the immense silicon infrastructure has become the dominant semi-conductor platform).

Step G explores innovation components. Once you have such a map, one can consider what is involved to progress along a given pathway to particular products, processes, or services, offered to particular markets. This should identify essential requirements for success that are not yet available. The process should also explore "how" those could be brought about. For instance, does a particular need call for government funding or standard setting? Are there requisite developments that call for partnering among which organizations? Figure 9 details a few issues (as an illustration) but the full map will have more (critical issues and potentially critical) issues that would need to be handled for successful innovation. For instance, what are the full life cycle costs of these various solar cell formulations?

Step H calls to Perform Technology Assessment. Much of the FIP process serves to promote the first type of Technology Assessment – evaluation of competing technologies. From Figure 1 onward, we are oriented towards the consideration of the target NEST with full awareness that it does not enter a vacuum, it doesn't have the market to itself. So how do the suggested NEST innovation pathways compare with alternatives? A first step is to broaden the Technology Assessment beyond the technology alone, but on the selection criteria outside of technical functionality. This leads us to the second type of Technology Assessment – impact assessment. We especially want to identify potential hazards and side-effects, including environmental, health and safety concerns that could arise. For solar cells, there are particularly toxic materials that could pose dangers during extraction, processing, and manufacturing processes. What sort of exposure issues are there? How do they compare with the risk and regulation landscape? Are the protocols for handling such substances in place? Is the risk framework adequate?

Additionally, are there materials apt to degrade into more toxic forms with extended exposure to sunlight and weather? What is to be done with the solar cells at the end of their useful life? On the other hand, and really interesting in FIP, is exploration of possible alternative, "unintended" application opportunities. Might the NEST's functional enhancements enable products in other markets? This has been illustrated by Robinson and Propp (2008), for the lab-on-a-chip platform.

Stage 4. Synthesize & Report.

These activities will take different forms and is related to why the FIP analysis is being done and for whom. Public sector oriented FIP would likely want to point toward suggested leverage points to promote a given family of innovations, or, as well, to preclude unintended costs. Robinson's studies typically provide reports and recommendations. Private sector FIP complements traditional CTI analyses, extending thinking toward strategic alternative pathway construction. FIP should inform the full sequence of developmental stages – from R&D portfolio selection, through new product development, various Open Innovation explorations, mergers & acquisitions with a technological aim, and so forth.

Various means could be used to integrate and communicate FIP findings. Socio-technical *scenarios* are especially appealing. These combine a large number of elements and dynamics relating to potential innovation chains. Lively story-telling can take actors' initiatives and interactions into account, and the surrounding or ensuing dynamics and shifts in agendas that slowly become irreversible. Scenarios are used here to provide insights into how plausible futures may unfold from the present, constructed in narratives that reflect innovation journeys. Were Figure 9's three simplified pathways to be fleshed out, they could provide key inputs. However, we would suggest that scenarios be written, not as is usually the case, as mutually exclusive alternatives, but as potential unfolding of the present into the future, where certain elements could be transferred into each other. In this way the scenarios are a role-play in text form that illustrate the challenges, opportunities, actors involved, and consequences of different paths taken, and the outcomes of co-evolution between actor strategies and the evolving innovation landscape.[19] We argue that scenarios are best used to promote in-depth consideration of managerial or policy options to advance particular innovations, not as forecasts of pathway likelihood. FIP can support such scenarios through showing in a visually concise way, the landscape of the expected futures on which these scenarios play out. FIP stimulates and informs decision making processes.

To wrap up, this is our second paper to present this approach (Figure 1) to Forecasting Innovation Pathways (see Robinson et al. in the References). That paper suggests ways that particular Future-oriented Technology Analysis techniques can contribute to the FIP steps. We are still refining the approach as we try it out on NEST cases. The variability among NEST situations and possible decision needs calls for the FIP approach to be considered as very flexible. The extent of data available, time horizon for innovation, and scope of study all reinforce the need to adapt these 10 steps to one's priorities. We hope that our FIP promotes the use of multiple information resources in conjunction with expert opinion.

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