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Abstract: This paper explores how to extract empirical knowledge from R&D, patent, and business literature compilations to help compose an innovation system model. It adapts the key elements and dynamics of “technology delivery system” modeling to a given Newly Emerging Science & Technology. We present a 10-step analytical approach to help characterize the technology, gauge its state of development, and depict the socio-technical system institutions and actors. We apply this to the case of Dye-Sensitized Solar Cells (“DSSCs”). A new “cross-charting” method appears effective at associating novel technology-enabled capabilities to gain functional advantages, and to link those functions to potential applications. The resulting systems model can help private and public sector decision-makers grasp key structures and processes, and how these can be tuned to enhance the prospects of successful innovation.

Keywords: emerging technology, technology delivery system, dye-sensitized solar cells (DSSCs), future-oriented technology analyses, technological innovation, newly emerging science & technology

1 Introduction

Effective management of technological innovation requires strategic perspective based upon sound empirical intelligence. Achieving that blend is especially challenging for “Newly Emerging Science & Technologies” (“NESTs”). This paper fills a gap by synthesizing an approach to 1) inform an innovation system model, by 2) drawing upon R&D data mining, for 3) NESTs. We introduce each of these elements briefly here, exploring them further later.

There are many innovation system models. We work with one family of these -- the Technology Delivery System (“TDS”). TDS modeling provides a useful framework within which to consider how certain enhanced technological capabilities can translate into a successful application (Ezra, 1975; Wenk and Kuehn, 1977). But to date, TDS conceptualizations have not been informed by systematic empirical findings (Roper et al., in press).

Findings from R&D text data mining and bibliometric analysis have largely stood on their own. They have not spoken directly to innovation prospects. We seek new mechanisms to derive findings from multiple types of R&D data and to link these to prospective applications.

“NESTs” are a loose category to which our European colleagues are drawing special attention (Jacobsson and Johnson, 2000; Foxon et al., 2005; Markard, 2006; Robinson and Propp, 2008). Classical technology forecasting methods were devised to address incrementally advancing technological systems (e.g., Moore’s Law well describes some six decades of semi-conductor-based advances). Those methods keyed on technical system parameters, somewhat more than on socio-economic system aspects. That is because they were initially driven by cold war considerations that concentrated on functional gains more than on cost and market issues. Today’s NESTs are more apt to incorporate science-based advances (e.g., biotechnologies; nanotechnologies), and those tend to occur sporadically, sometimes with disruptive effects. NEST analyses often concern economic opportunities, with significant concern to identify and mitigate potential “unintended, indirect, and delayed” societal consequences. We seek to contribute to development of analytical tools to relate early stage scientific advances to long term implications (i.e., potential applications and their implications).
These three threads come together as a research question -- how can we better exploit R&D information resources concerning NESTs to identify innovation opportunities? We address this question by combining quantitative (empirical) and qualitative analyses. We strive to offer the technology policy-maker or manager a systems model that incorporates empirical intelligence on key players, leverage points, and requirements.

We exemplify our approach for a particular NEST case. Nanotechnology concerns engineering matter at molecular scale. It has great potential to apply new materials and devices in novel applications. Within the context of ongoing empirical analyses of nanotechnology ("nano") R&D, we focus on how nano materials are being used to enhance the performance of solar cells, an important renewable energy technology form (also known as photovoltaics). Dye-Sensitized Solar Cells ("DSSCs") are one type of nano-enabled solar cells with special promise. DSSCs are made of low cost materials and are less equipment-intensive than other solar cell technologies. Mining R&D information resources to help anticipate DSSC innovation pathways can provide value for R&D managers in setting priorities, new product managers in composing development teams, and national policy-makers in helping to formulate economic infrastructures to encourage innovation. The driving question here is – can we compose an empirically grounded technology delivery system that informs DSSC development prospects?

The following Background section reviews TDS modeling, "Tech Mining," and the NEST of special concern – DSSCs. Section 3 presents our 10-step approach; then Section 4 describes the methods and data resources used here. Section 5 consists of the main case analysis, applying our approach to DSSCs. Section 6 concludes.

2 Background

2.1 Technology Innovation Systems Modeling

A variety of approaches aim to capture the systemic processes by which emerging technologies contribute to commercial innovation; we mention only a few. Hekkert et al. (2007) key on "functions of innovation systems." Some researchers look into what kind of innovation transfer is most effective -- e.g. O’Shea et al. (2008); Liu et al. (2008). Early identification of likely innovations can help discern opportunities, foster energy transitions, and foresee societal impacts -- beneficial, as well as undesirable -- while the course of technology development remains more malleable (Collingridge 1980; van Merkerk and van Lente 2005).

We note several innovation system modeling efforts pertaining particularly to energy technology, given our case focus on solar cells. Several scholars seek to understand the driving forces and the blocking mechanisms that influence development and diffusion of sustainable technologies (Jacobsson and Johnson 2000; Foxon et al. 2005; Markard 2006; Negro and Hekkert 2008; Negro et al. 2007; Negro and Suur 2008). Stephens et al. (2008) offer a state-level, socio-political system framework to analyze energy technology deployment. Meijer et al. (2007) address the influence of perceived uncertainty on the development of emerging renewable energy technologies.

Among various approaches to capture the essentials of innovation systems, the Technology Delivery System ("TDS") has demonstrated value by capturing and representing key enterprise and contextual factors. Wenk and Kueh (1977) advance TDS as a form of socio-technical systems modeling to help identify the pivotal elements involved in innovation. By "innovation," we mean a novel technical contribution effectively translated into a successful product or process (i.e., commercialization).

In a classic case, Ezra (1975) offered a TDS to help explain why solar energy innovation in residential housing applications was not notably successful, despite major US Government funding of solar R&D in the national labs and universities in the wake of the OPEC oil crisis. By sketching key institutional actors and relationships he identified at least five challenges. For instance, national lab researchers lacked incentives for technology transfer (later legislation addressed this); no single enterprise could implement solar panels (e.g., equipment manufacturers don’t build houses); home builders are inordinately distributed and risk-adverse; and multiple, weakly coordinated regulatory regimes would need to be met (local authorities have different building codes).

The elements that appear in a TDS model change from application to application. For instance, Shi et al. (1985) developed a TDS for microcomputer technology in developing countries, spotlighting the importance of language barriers. TDS models can serve to identify the key institutional actors, spelling out enterprise requirements, and spotlighting leverage points to affect the prospects of successful commercialization.
Kuehn developed a TDS at the Jet Propulsion Lab that aided in designing and implementing the $100 million/year Department of Energy photovoltaics and solar thermal program. The TDS effort facilitated design of the first generations of solar technology, including pilot and demonstration plants, and technology transfer mechanisms. [Thomas J. Kuehn, personal communication (Sep. 8, 2009)]

The TDS approach is akin to other technology innovation systems approaches noted, but we favor its distinct treatment of 1) the enterprise (organizations with requisite capabilities) to develop the innovation and take it to market, and 2) the key contextual factors (actors, trends & events) affecting the success of that innovation process. Clear understanding of both set of factors offers a valuable decision aid to inform successful NEST management.

2.2 Tech Mining and Future-oriented Technology Analyses
Bibliometrics – counting activity levels and identifying patterns in R&D bibliographic records, plus patent analyses -- have contributed to science & technology studies for decades (c.f., van Raan, 1988; Moed et al. 2005). With the expansion of databases that compile abstract records and of desktop computing power, text mining of those records further enriches the empirical base. “Tech Mining” (Porter and Cunningham 2005) is our shorthand for such activities.

“Research profiling” (Porter et al. 2002) examines a technology of interest by search and retrieval of abstract records on the topic. This can help researchers and research managers understand the “research landscape” to identify what is already heavily studied, to help ascertain the best opportunities for one’s own research. This can also uncover discoveries in adjacent fields and new tools that might be adapted to one’s purposes.

What has been lacking is a systematic way to compile this intelligence on a given NEST to inform innovation management. So, we take additional steps with such compilations of research articles, patents, and so forth. We scour those records, with the help of text mining software (we use VantagePoint – see www.theVantagePoint.com), to uncover mentions of possible applications and issues downstream. We also identify active organizations. As Section 5 exemplifies, we also work to relate the content of the data searches to particular innovation process aspects.

Future-oriented Technology Analyses (“FTA” – see: forera.jrc.ec.europa.eu/fta_2008/intro.html) include within their purview, increasingly science-based technologies, with less orderly developmental trajectories (c.f., Technology Futures Analysis Methods Working Group 2004; Cagnin et al., 2008). The analytical components that we address should be considered in the context of performing FTA.

2.3 Dye Sensitized Solar Cells
Our case study reflects an intersection of interests in NESTs, nanotechnology, and renewable energy. We offer this not as a comprehensive analysis that could guide DSSC policy or management, but to illustrate how a TDS model can be conformed for an emerging technology under scrutiny.

Growing environmental, economic, and geo-political concerns with the current energy system press for changes (Roberts 2004; Stern 2006). This offers special opportunities for emerging renewable technologies. However, large-scale implementation of emerging renewable energy technologies has proven challenging (Jacobsson and Bergek 2004; Negro 2007; Raven 2005). To facilitate such a transformation, policy makers and others need to understand the key processes in the development, diffusion, and utilization of these NESTs (Bergek et al. 2008).

Our group at Georgia Tech has been compiling extensive sets of nano R&D records from several databases (c.f., Porter et al., 2007) and performing multiple analyses (c.f., http://www.nanopolicy.gatech.edu/). Since 2009, we have focused on particular sub-topics within nano. This paper reflects an ongoing effort to understand nano-enhanced solar cells. Solar cells can be characterized in three developmental generations (e.g. Conibeer 2007; Green 2003). 1st G -- First Generation--- “Conventional Solar Cells”, made in crystalline silicon, account for ~90% of the market, but these are expensive. 2nd G -- 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. 3rd G -- 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.”

Several 2nd and 3rd G technologies pursue nano means to advance solar cell performance. “Dye-Sensitized Solar Cells” (“DSSC”), invented by O’Regan and Grätzel (1991), constitute perhaps the most promising and, so far, the most efficient of all solar cells that employ nanotechnology (Aydil 2007). Appendix A introduces DSSC basics. Although DSSC commercialization is still in its infancy, many technical papers anticipate fascinating prospects – c.f., Aydil (2007), Lenzmann and Kroon (2007), Snaitl and Schmidt-Mende (2007), and Grätzel (2003).

This situation highlights the complexity of NEST innovation processes. Some emerging technologies are totally new, with no existing markets. Others advance improvements into an existing market. DSSCs are just entering the market (so data are minimal), yet the solar cell market does have a track record.

To assess the innovation prospects for DSSCs, we need to relate to energy opportunities generally, focusing on solar cells (i.e., photovoltaics). Relatively mature solar cell technologies have established markets – and they continue to advance their performance. In some respects the solar cell family collaborates (e.g., in pushing for governmental R&D funding, tax subsidies, and favorable regulations); in other respects, they compete (i.e., in the marketplace).

3 A 10-Step Process to Compose an Empirically-based Technology Delivery System

As mentioned, analyzing NESTs presents challenges in that they vary greatly in the extent of available track records on both the technology development and commercialization sides. Composing an innovation system model is vital to formulating effective policy and development strategy.

Analysis of an emerging technology should elucidate technology policy & management issues and questions. Porter and Cunningham (2005) list 39 tech mining questions and more than 200 indicators based on 13 Management Of Technology (“MOT”) issues. These are just suggestive; the technology analysts need to work with the intended study users to determine what information, in what form, would be most valuable in managing the technology in question. For emerging NESTs, candidate questions to answer include: Does this technology offer realistic innovation potential? What is driving such innovation? Are there potential unintended consequences of manufacturing and introducing the resulting products (or processes)?

Helping answer such questions -- suitably tailored to one’s NEST and managerial responsibilities -- is the aim of our 10-step analytical process (Fig. 1). We letter (rather than number) the steps, A-J, to downplay their linearity. Insights on particular system components contribute to understanding others, but feedback links are not drawn in as the model becomes cluttered. Note that Step J (on the right side), Expert Checking, contributes throughout the modeling process. The degree of work on a given element will vary considerably from study to study. We introduce the ten elements here; the case study then illustrates how to perform them and their content.
A. Specify the Management of Technology questions

B. Understand the new and emerging S&T

C. Profile R&D: S&T push

D. Assess Market Needs: Demand pull

E. Cross-charting: from research outputs to Applications

F. Technology assessment

G. Internal actor analyses

H. External actor analyses

I. Compose the TDS

**Fig. 1.** Ten step process to compose a TDS for a Newly Emerging Science & Technology [NEST]

A. **Specify the MOT questions**: This step frames the study. It demands interaction between the analysts and target study users. Such interaction should address all ten elements to orient the study and to enhance prospects for utilization.

B. **Understand the NEST**: This facilitates all following activities (e.g., database searches), identifies vital information, and helps bound the study. Our experience suggests first trying to locate overview articles and run initial searches to gather technology-related information. Then, check one’s initial characterizations with one or two local persons knowledgeable about the technology.

C. **Profile R&D**: Our “Tech Mining” approach entails searching in one or a few major Science, Technology & Innovation (“ST&I”) databases to identify the extent and nature of research pertaining to the technology (Kostoff et al. 2008). In conjunction with Step D, we seek to learn who are the key researchers, what are they doing, and what advances can be anticipated. These help understand “S&T Push.”

D. **Assess Market Needs**: Following Schon (1967), technological innovations can be distinguished as primarily driven by technological advances or by market pull, or sometimes a combination (Chau and Tam 2000). In conjunction with Step C, we seek information on markets (e.g., the share held by different products or processes), and how the markets might welcome innovations based on the emerging technology. This helps understand “Demand Pull.”

E. **Cross-charting**: We seek to link new technologies to enhanced functions. We then strive to relate those functions to potential applications. Those applications can be associated with target users and most promising markets. This “cross-charting” also helps discern technology system requirements to accomplish particular applications (as per Ezra’s TDS). Results help see the advantages of the emerging technology versus key competing technologies. These several information elements also help identify key TDS institutions.

F. **Technology Assessment**: Two meanings of “technology assessment” have emerged. One concerns the evaluation of alternative technologies—i.e., comparing current technologies in terms of specific objectives (our key concern). The second refers to assessing impacts – studying the future broad, societal effects of emerging technologies (Porter et al. 1991).

G. **Internal actor analyses**: We seek to identify the main actors who would “deliver” the technological innovations under study. We want to know the key organizations, the nature of their interactions, their strengths and weaknesses. Where we determine gaps in requisite capabilities, we want to identify how those could be remedied.
H: External actor analyses: We are concerned with environmental influences that can critically influence, or be influenced by, the process of emergence, diffusion, and application of the technology. The competitive environment is critical for an emerging technology. How will it fit in or supersede existing technological systems? Incumbent infrastructures (physical and institutional) may be malleable, but usually favor established technologies and resist intruders (Jacobsson and Johnson 2000).

I: Compose the TDS: In this step, we consolidate the knowledge acquired in the previous steps to portray the enterprise and key contextual elements of the TDS. In addition, we depict the processes through which those elements interact — e.g., flows of influence, funding, and knowledge pursuant to delivery of the innovation.

J: Expert Checking: Expert opinion methods are essential to Future-oriented Technology Analyses (“FTA”). Often, FTA entails formalized approaches (e.g., Delphi). Here we mean informal, interactive engagement of a few knowledgeable persons. Technical experts help understand the technology, formulate database searching, and interpret findings. Business experts help characterize the critical success factors and barriers to be overcome for the emerging innovation to succeed. Nearby location facilitates interaction. Bibliometric searches can identify candidate experts. One-on-one and informal group workshops can contribute richly (Robinson and Propp 2008). As Fig. 1 implies, expert checking should be done throughout the course of the analyses.

4 Methods and Data

We apply three main methods: literature search, expert engagement, and bibliometric analyses. Bibliometric analyses mainly inform Steps C (Profile R&D), E (Cross-charting), and G (Internal actor analyses). Literature search and expert engagement contribute to most every Step. “Expert checking” is very important throughout. Our approach in this paper combines qualitative (reading key literature and interacting with knowledgeable people) and quantitative (data mining) methods.

Multiple bibliometric sources enrich understanding the TDS. As Martino (2003) notes, the Science Citation Index (SCI data) represents fundamental research activity, whereas other databases tap more applied research and development. We searched SCI and engineering-oriented EI Compendex. As development progresses, patent databases (e.g., Derwent World Patent Index - “DWPI”), become key. Business and popular press abstract sources (e.g., Factiva) then help characterize commercialization activities.

For the DSSC case, we extract abstract records published from 1991-2009 that indicate some variation of “dye-sensitized” solar cell focus in the topical fields. We also get DSSC abstracts for these years from Compendex, DWPI, and Factiva.1

5 Case Analysis: Dye-sensitized solar cells (“DSSCs”)

Within the scope of this case study, our purpose is to present the 10-step analytical process, rather than attempting a complete innovation forecast for DSSCs. Additional research profiling and analyses for nanoevolved solar cells appear elsewhere (Guo et al., 2009a; 2009b; 2010). We now consider the 10 steps (Fig. 1), with illustrations from the case analysis.

A. Specify the MOT questions
For DSSCs, we key on three MOT questions (Porter and Cunningham 2005). We seek to find out about: What are the most promising DSSC applications? Do those pose potentially serious environmental or societal impacts? Who are the key players in potential DSSC innovation processes?

Were one to key on different technology policy or management questions, content would vary accordingly.

B. Understand the NEST
Section 2 highlighted a few essentials of DSSCs and the solar cell family of technologies. Our focus on DSSCs evolved over 10 months that began with interest in how nanotechnology could enhance solar cells. Bibliometric

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1 Boolean search phrasing is like this for EI Compendex: (((dye-sensitized or dye-sensitised or "dye sensitized" or "dye sensitised" or DSSC) WN KY) AND ((DSSC or "solar cell" or "solar cells" or photovoltaic or photovoltaics or photoelectrode or photoelectrochem* or photocurrent) WN KY)). We did discover a few other uses of “DSSC” (especially in telecommunications) and removed those records.
analyses showed DSSCs to be an active research arena, prompting further probing. Literature review, with guidance and interpretation from Georgia Tech colleagues (Prof. Jud Ready, Dr. Wenjie Mai, and PhD candidate Chen Xu), refined our understanding (Guo et al. 2009). This led to investigation of DSSCs as a particularly promising NEST.

Specifying this seemingly obvious step entailed rethinking our process. Previously, we had concentrated on research profiling, at the front end (Porter et al. 2002), and answering user questions at the back end (Porter and Cunningham 2005). The importance of understanding the technology led us to recruit Chen Xu to our DSSC analytical team (a vital component of our Step J – Expert Checking).

C: Profile R&D
This activity draws heavily on bibliometric and text mining analyses of the database search results. We refrain from presenting the R&D profiling per se here (see Guo et al., 2009b), rather preferring to focus on how we extract empirical knowledge to inform the TDS modeling and to help understand potential DSSC applications.

“Tech Mining” the various publication and patent abstract records can track the emergence of key terms over time to spotlight new (appearing only in the most recent time period) and hot sub-technologies (i.e., those appearing more frequently in the most recent time period). Extracting the organizational entities -- particularly of those publishing R&D articles, those patenting, and those being discussed in the business-oriented literature – identifies possibly important actors in the DSSC arena. Mapping research networks identifies collaborations. To give the flavor, we focus here mainly on the SCI research publications, selectively presenting results from analyses of Compendex, DWPI, and Factiva search sets.

We begin by showing trends based on the annual activity from each database in Fig. 2. It is clear that the publications from all four databases are ascending strongly – interest in DSSCs is increasing exponentially these past several years. Recently, the number of publications emphasizing engineering (Compendex) climbs to exceed more fundamental research (SCI publications) – suggestive of increasing prospects for innovation. Patent activity is accelerating (because the patent granting process takes years in most authorities, it is hard to estimate how many patents will be granted in recent years, so 2008 and 2009 are not shown for the priority patents plotted here). Again, this lends credence to likely applications emerging. And, finally, business attention has accelerated dramatically from 2008. These trends suggest recent maturation of DSSC technology, which could imply impending commercialization.
Fig. 2. Dye-sensitized solar cells publication & patent trends

We also note the top countries authoring DSSC research publications in SCI (not shown here) -- Japan (308) is at the top, followed by China (205), the USA (167), Switzerland (132), and South Korea (114). This implies that an international focus is essential to anticipate DSSC innovation.

Table 1 shows the “top 10” research organizations pursuing DSSC research. “Countries” reflects their degree of international collaboration (i.e., tabulating co-author nationalities). “% since 2006” is an indicator of how recent this organization’s DSSC research is. Examining the emphases of the research can alert one to potential research fronts. For our purposes, these organizations are one important set of players in the DSSC innovation system.

The Chinese Academy of Science (“CAS”) stands out as the most active research organization (albeit with many separate institutes). CAS is very important for China’s DSSC R&D, as it has 88 of some 200 publications. CAS has published 52% of its 88 papers since 2006, which implies ongoing DSSC emphasis. As for Switzerland, we found Grätzel is the leading author for both the “Swiss Federal Institute of Technology” and “Ecole Polytechnique Federal de Lausanne (EPFL).” Grätzel is an author of 114 of Switzerland’s 135 papers.

Compared with other countries, DSSC research in Japan is more dispersed. Three Japanese organizations appear in the top 10. The Institute of Fundamental Studies is a Sri Lankan organization, that has conducted nearly all of that country’s DSSC research (38 of 48 papers), much in cooperation with Japanese colleagues. The National Renewable Energy Laboratory (NREL) is the only US organization in the top 10.

Table 1 Top 10 DSSC Research Organizations
[Based on the Science Citation Index]

<table>
<thead>
<tr>
<th>Affiliation (Name Only)</th>
<th>Top Countries</th>
<th>% since 2006</th>
<th>Research emphases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chinese Academy of Science</td>
<td>China [88]</td>
<td>Japan [6]</td>
<td>52% of 88</td>
</tr>
<tr>
<td>Institute of Fundamental Studies</td>
<td>SRI LANKA [38]</td>
<td>Japan [18]</td>
<td>USA [4]</td>
</tr>
</tbody>
</table>
Relating to TDS modeling, no corporations appear among the top 10 DSSC organizations in SCI. Not surprising as fundamental research is typically dominated by publicly funded research institutions (Miyazaki and Islam, 2007). In an upcoming section, we explore cooperation between the public and private sectors, which can be vital to research knowledge diffusion. In sum, the energetic increase in DSSC research in recent years supports the notion of a significant “S&T push” for commercialization of the fruits of that research.

D: Assess Market Needs

Here, we seek data on the solar cell market, considering the potential demand for DSSCs within this arena. One could scale up to consider the overall energy market, but because DSSCs hold only a tiny share within the solar cell market, we focus at that level.

Most solar cell production (90% in 2007) has involved 1st G silicon solar cells. 2nd and 3rd G solar cells are expected to gain a much larger share of this solar cell (photovoltaic – “PV”) market. DSSCs are estimated to take just 0.01% of the market in 2010 – truly a “new” emerging technology. Long-range projections point to a possible 3% of the solar cell market in 2030 for DSSCs, with much higher potential in the 2040s (Shi, 2007).

We turn to the literature to gain market understanding. Macias (2008) divides the solar cell market into three sectors. Grid-connected systems dominate the current market for solar cells (>90%). Here solar cells can be installed on top of a roof or integrated into the roofs and facades of houses, offices, and public buildings. Off-grid systems account for approximately 4% of global photovoltaic installations in 2007. Here, solar cells provide vital power for communities in the developing world that lack access to electric grids. Third, solar cells are used in a wide range of consumer products and small electrical appliances -- in 2007, roughly 1% of global photovoltaic sales.

DSSCs are especially attractive for Building-Integrated Photovoltaics (BIPV) because the color of the device can be easily varied by choosing different dyes and building cells on flexible substrates (already demonstrated). These could suit both grid-connected and off-grid systems. DSSC technology also has special potential for lightweight, portable, power-supply charging devices for consumer electronics and military applications (e.g., mobile telephones and military garments) (Matson 2007).

We have strong reason to believe that long-term demand for solar cells will increase strongly. While that demand is not expressly for DSSCs, their combination of high performance potential with color and flexibility, suggest strong potential “demand pull.”

E: Cross-charting

Here we relate research emphases to attributes that could contribute to improved solar cell functionality, and, in turn, to improved products. In DSSCs, nanostructured materials are key because they provide the large surface area for dye adsorption (Aydil, 2007). So, we start with nanomaterial advances. A solar cell made using nanostructures gives approximately 1000 times the current of a solar cell made from a TiO₂ “thin film” (titanium dioxide is the most prominent material in DSSCs) covered with a monolayer of dye.

Currently, two categories of nanostructures are being most investigated in DSSC R&D: nanoparticles (“zero-dimensional” structures) and nanowires (“one-dimensional”). DSSC research started with nanoparticles (TiO₂). TiO₂ nanoparticle DSSCs represent almost 80% of recent research activity. However, researchers have found that the photogenerated electrons make millions of “hops” among nanoparticles as they travel through the porous TiO₂ film to the transparent electrode. These hops slow down the electron transport and increase the
chances of electron recombination. Several researchers have been pursuing the use of nanowires or nanotubes (especially ZnO), instead of nanoparticles, to decrease the electron transport time.

Quantum dots and carbon nanotubes are special cases of nanoparticles and nanowires, respectively, that offer advantages. Quantum dots are small enough to tailor the optical properties that arise as a result of quantum confinement of materials. Several proposed designs use quantum dots -- one interesting option is to take the place of the dye.

Fig. 3 illustrates one of several “cross-charts” we have generated. The basic idea is to take one set of items and relate it to the next, and so forth. One adjusts those sets depending on the study foci (Step A) and the nature of the technology and market dimensions (especially, Steps C, D, and F). We don’t show the general one that includes many prominent technical elements, functions, and applications – it shows that developments contribute broadly to functions and applications. Fig. 3 illustrates how one can explore a particular application (e.g., glass structures as a special case of BIPVs) to investigate which materials and functions could contribute strongly to that development. Stepping through the five segments of Fig. 3:

1) Novel research-based contributions [here, focus is placed on nanomaterials]
2) Solar cell types [here we only illustrate for DSSCs]
3) Features [keying on those most useful for product attributes contributing to glass structures]
4) Product Attributes
5) Potential Market [here focusing on one specialty area]

Cross-charting offers perspective on how specialized the innovation paths ahead might be. At one “neat” extreme, one might see specialization -- each research contribution relating to a single function, that served one key application, that would serve a single market. At the other extreme, imagine every research contribution significantly aiding every important function, in turn advancing a diverse set of applications. That would point toward high pressure for integration of technology (e.g., possibly toward common platforms) and of
organizations (e.g., if investing in developing the technology serves multiple potential markets via a wide array of products). In the DSSC case, energy applications dominate. [That might have helped focus on particular key organizations and markets, to think through likely innovation pathways.]

Cross-charting is also useful in engaging experts. Questions they can help answer include: have we identified the important functions? Have we grouped those functions sensibly? What are important distinctions among applications?

**F. Technology Assessment**

DSSCs are a promising solar technology, but compared with other photovoltaic technologies, DSSCs are at an early developmental stage. The first form of Technology Assessment ("TA") seeks to determine how DSSCs compare with competing energy technologies in terms of cost, efficiency, applicability, and sustainability. [This section draws heavily upon McConnell (2002); Bossert, et al. (2000), and Grätzel (2003), with helpful expert checking.]

DSSCs have unique advantages. Cost, the most important one, is about $2/watt, and that is 50% less than silicon-based solar cells ($3/watt). Production facilities are much cheaper than for silicon-based solar cells. The major materials in DSSCs -- TiO$_2$ and ZnO -- are quite biocompatible compared to silicon, upon which 1st G solar cells rely. DSSCs also offer light weight, flexibility, transparency, and color options that are very attractive compared with other solar cell technologies. Also, DSSCs can be used directly to produce high-energy chemicals from sunlight. Such “photosynthetic” devices neatly solve the challenge of finding sufficient energy storage.

However, in other aspects, DSSCs compare less favorably with silicon-based and other solar cells. DSSC light conversion efficiency presently lags. Recent research on efficiency focuses on using quantum dots for conversion of higher-energy (higher frequency) light into multiple electrons, using solid-state electrolytes for better temperature response, and changing the doping of the TiO$_2$ to better match the electrolyte being used. Potential efficiency appears to be 20% (Grätzel 2003). The solid-state electrolytes also solve the problem of long-term stability. With the increase of efficiency and stability, DSSCs could be a great replacement option for existing technologies in "low density" applications, such as mobile phone chargers.

As mentioned, we believe both definitions of TA pertain. We have explored the technology comparison version here. We have not systematically explored the impact assessment form of TA -- i.e., to identify potential unintended, indirect, or delayed effects of introducing DSSCs via various applications. That remains to be done -- e.g., to check for potential environmental or health implications of titanium dioxide particles, and DSSC production, distribution, and eventual disposal.

**G. Internal actor analyses**

Who are likely to be important players in “delivering” DSSC technology to market? [The next section identifies important contextual players.] Again, we must decide how broadly to focus. We key on DSSCs, and emphasize R&D and production, as these involve important distinctions from traditional solar cells. Some actors whom we could include in a broader treatment of solar cell innovation are silicon wafer producers, solar cell production machinery manufacturers, engineering firms designing solar energy systems, electric companies, and builders (recall the Ezra, 1975, TDS for solar home building applications).

Table 1 noted prominent DSSC research organizations, dominated by universities and government labs. Which organizations might likely pursue commercialization of DSSCs? We gain three vantage points on companies engaging DSSCs: those publishing DSSC research; those patenting, and those active in the business arena. Table 2 lists the top companies from three data sources, respectively reflecting each perspective. We note a few interesting points. Japanese companies are prominent, especially in research. China, the second most prolific country in research publication, shows no notable company activity. Some companies publish; some patent; a few show prominently in both (Samsung, Sony). The Factiva search, tapping business activity, finds some of the same players and some different -- i.e., not publishing or patenting (e.g., Dyesol, G24 Innovations -- relating to their products, whereas Sony and Sharp appear in Factiva for their research).

Table 2 Top DSSC companies based on three data perspectives
One way to utilize the R&D data is to generate social network analyses. We have done so for the SCI data, expressly to see the connections between active companies and particular universities. For instance, that spotlighted that Samsung is collaborating with several university groups on DSSC research (Guo et al. 2009b).

Further network analyses can ferret out potentially important connections. To illustrate, let’s focus on the companies that are noted as pursuing commercial production of DSSCs. Three stand out in the Factiva compilation (taking note of those active in R&D and patenting from the other databases too): G24 Innovations, Konarka Technologies, Inc., and Dyesol Ltd. [Appendix B describes each.] Fig. 4 shows relationships among these and other institutional actors. G24 Innovations is producing DSSCs commercially, whereas Konarka is licensing related intellectual property. The Australian company, Dyesol Ltd., has notable ties to EPFL, the Swiss university prominent in Table 1.

![Diagram of DSSC players and others](image-url)

**Fig. 4.** Relations among three interesting DSSC players and others
The actors identified in this section could prove important players in a DSSC “delivery system,” but Table 2 reminds that there are a number of other strong candidates. A company pursuing DSSCs or a competitive technology would want to monitor such players. By no means would one assume that organizations’ roles are fully defined by this empirical information – one must check and enrich this “competitive technical intelligence” through human expertise.

H. External actor analyses
Here, we want to learn about forces and factors currently or potentially affecting NEST development. This means monitoring the competitive environment, government policies, regulations, stakeholders, and public interests.

Taking a broad perspective, the earth’s rising energy demands, combined with global warming and environmental pollution concerns, and declining fossil fuel supplies, mandate long term commitment to renewable energy. Sunlight provides, by far, the largest of all carbon-neutral energy sources. More energy from sunlight strikes the Earth in one hour ($4.3 \times 10^{20}$ J) than all the energy consumed on the planet in a year ($4.1 \times 10^{20}$ J). Solar power is a $7.5$ billion industry growing at a rate of 35–40% per annum (Lewis, 2005). The huge gap between our present use of solar energy and its enormous potential supports solar solutions, including DSSCs.

Government funding and policies are key external factors in the “solar system.” At least 11 European Union (EU) member states offer subsidies for solar power, with instruments ranging from feed-in tariffs to investment grants and subsidies, tax credits, and beneficial credit terms. Recently, the US enacted the “American Recovery and Reinvestment Act of 2009 (ARRA 2009)” with provisions to help energy generation businesses, including solar energy. Not much government policy directly focuses on DSSCs, but government agencies fund and/or perform R&D. For example, the US National Renewable Energy Lab is pursuing solar cell R&D (Matson 2007). The government also supports private R&D – e.g., Konarka Technologies has received such support [gleaned from the Factiva abstracts].

Within the solar energy market, crystalline, silicon-based solar cells dominate. DSSCs must compete with these 1st G solar cells, as well as with other new & emerging PV forms. The relatively mature silicon solar cells benefit from other forces that advance silicon technologies (i.e., the semiconductor industry). Despite their issues (especially environmental), prevailing wisdom is that silicon-based solar cells will not be completely replaced in the foreseeable future. However, emerging solar cell technologies have strong prospects of sharing in an expanding solar cell market.

In other technology systems where new forms advance, while mature ones co-exist, sometimes the same companies develop both. That takes advantage of market know-how and distribution networks. In other systems (e.g., think of digital watches), different companies enter from outside with the new technology. Monitoring the wider competitive environment for DSSCs is vital for those considering investment.

I. Compose the TDS
Fig. 5 presents our digest of the preceding stepwise analyses. In terms of the enterprise to accomplish commercial innovation based on DSSC technology, we sketch three loose groups of companies based on our suggestive analyses (c.f., Table 2). We note relatively few of those companies “doing it all” – i.e., publicly researching, patenting, and openly pursuing business opportunities. Fig. 5 identifies three small companies especially active in DSSC business promotion. Table 2 reminds that the stage could alter abruptly should one or more multinationals (e.g., Sony) determine to pursue major development.
Fig. 5. TDS for DSSCs

Fig. 5 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 favor innovation, but the short term global economic malaise has hit the solar cell market hard. Our assessment of the competitor solar cells finds that DSSCs currently hold a minuscule share of the market, but hold bright prospects. This TDS offers input to further expert deliberations.

**J. Expert Checking**

As mentioned, this works well on an ongoing, informal basis. We have been fortunate to engage several Georgia Tech colleagues intermittently as we work through the nine steps (with expert checking as the tenth). They contributed especially to Steps B, E, and F. Our expert input culminated in a Georgia Tech workshop (Fall, 2009). We assembled colleagues from the departments of materials engineering, chemistry, policy, etc., who engage different aspects of nano solar cells R&D. The workshop aimed to review and refine the existing analyses and to explore promising innovation pathways.

In reflecting on DSSC innovation pathways, a pivotal consideration is whether these are likely to be relatively specialized or not. The specialized model would have distinct actors (organizations) pursuing singular applications. The alternative, generalized or “platform” model would posit core development from which myriad different applications could branch out. We are still analyzing these possibilities.

The workshop also provided particular considerations of how given attributes could translate into application advantages. For instance, our knowledgeable participants identified “flexibility” as an especially advantageous characteristic for solar cell applications. One could focus on this to explore commercial opportunities, and then track back (as per Fig. 3) to identify the most promising technical means to achieve flexibility, the leading researchers, and the potentially interested enterprises to deliver innovations to selected market niches.

**6 Conclusions**

This paper synthesizes an approach to inform a NEST innovation system model by drawing upon R&D data mining. We believe that evidence-based Technology Delivery System modeling contributes to understanding the dynamics of NEST innovation systems. The TDS brings together key components and considers how they relate as a system to deliver commercial products. Our workshop found this conceptual modeling fruitful in
thinking about non-technical requirements to achieve successful innovation for our case of Dye-Sensitized Solar Cells.

The paper offers a 10-step approach to integrate information from R&D data resources with literature content and expert knowledge to help compose a TDS model. This process blends quantitative and qualitative methods. In particular, our cross-charting method helps relate R&D advances to functional gains that they can provide, and, then, to potential applications. Starting with one’s key asset(s), cross-charting can help identify potentially relevant “upstream” elements to monitor and “downstream” opportunities to pursue. In so doing, it also helps to ascertain key actors (i.e., institutions) (Fig. 3) to engage. Cross-charting could inform Technology Roadmapping endeavors, which is used for communicating the relationships between evolving and developing markets, products and technologies over time (Phaal et al. 2004). We continue to explore how cross-charting can apply at various granularities (e.g., to explore opportunities for a specific technological advance within a NEST vs. those for a new technology or new application). We also are pursuing ways to apply “Tech Mining” methods such as specialized thesauri and identification of “triples” (subject-verb-object) to facilitate composing cross-chart linkages.

Ezra’s (1975) TDS pointed out factors impeding successful innovation in the 1970’s residential solar market. Our DSSC TDS is only a test case, so our aspirations were modest. Nonetheless, it serves to identify extremely optimistic market potential, but stilt solar cell (and other energy forms) competition within that market. The early DSSC players are relatively small firms, whereas the dominant solar cell technology involves very large firms and an entrenched silicon infrastructure, underwritten by the enormous semiconductor industry. Unlike Ezra’s TDS, here we do not see extreme barriers to taking this technology to market (e.g., regulations, fractured industrial system). We find a generally supportive public environment.

We contrast the information resources available today to those when Ezra addressed solar energy innovation in 1975. Our analytical approach takes advantage of the rich repositories of electronic information to profile R&D and to understand business activities pertaining to the NEST in question – i.e., we “tech mine” via database searches and analyses of the retrieved records. We integrate these empirical sources into our 10-step approach to enrich earlier, largely qualitative TDS modeling. That said, this exercise aimed at refining our analytical approach to gauge future prospects for NESTs. The result is our 10-step approach. Certainly, one could adapt this in various regards. It is important to specify the driving needs to understand the particular NEST under scrutiny. An FTA practitioner cannot step in and assess “any” technology without aid from topical and business experts. We believe that the 10-step TDS approach will adapt well to other NESTs. We caution that it is not a linear recipe. It invites cross-disciplinary knowledge contributions because all can grasp the model readily. And it can provide results that managers and policymakers can understand readily.

TDS modeling is an FTA tool. It can be used to inform decisions at various levels and with various foci. Consider two of many decision perspectives possible concerning DSSC development:

- National policy – here, DSSCs offer one renewable energy option, to be weighed together with other technologies, national resources and priorities – i.e., the DSSC TDS would provide one piece of a larger puzzle.
- Company product development – a given company could be a technology developer (e.g., holding key DSSC patents) or an energy provider (marketing one or more options). Depending on their roles and interests, they would devise markedly different TDS models. For instance, one might key on university and company technology component providers (potential partners); another might key on competing energy forms for a certain market (as specific as greenhouses or as broad as all built environments). A company DSSC TDS could focus on enterprise requirements analysis and/or target external actor relationships.

What these have in common is an easily understood framework to weigh technological and contextual factors together to manage innovation processes. Here, we offer ways to incorporate richer empirical information into the innovation system modeling.

**Acknowledgements**

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findings and observations contained in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors appreciate the valuable suggestions from Prof. Jud Ready and Dr. Wenjie Mai (both at Georgia Tech).

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Appendix A How DSSCs Work

They reflect the generic design shown in Fig. 6. Material A consists of titanium dioxide (TiO$_2$) nanoparticles abutted against each other to form a porous film approximately ten microns thick. A single molecular layer of a photosensitized dye (material C) is adsorbed on the surfaces of the TiO$_2$ nanoparticles and the pores are filled with an electrolyte (material B) containing a redox couple(I$_3^-$/I$_-$). The nanoparticles with the dye and the electrolyte are sandwiched between two transparent conducting electrodes and sealed to prevent the electrolyte from evaporating.

Fig. A.1. Typical DSSC design (source: Aydil, 2007)

As light is absorbed by the dye, an electron is excited to a higher energy level. This excited electron is rapidly injected into the TiO$_2$ nanoparticles and travels to one of the DSSC electrodes by hopping from one particle to another, thereby generating a current. The positively charged dye undergoes an electrochemical reaction with I$^-$ in the electrolyte to form I$_3^-$ which shuttles the “the hole” to the counter electrode where it is reduced back to I$^-$ to repeat the cycle.

Appendix B Information on the 3 Key Companies Based on DSSC Business Activity

<table>
<thead>
<tr>
<th>Name</th>
<th>G24 Innovations</th>
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<tbody>
<tr>
<td>URL</td>
<td><a href="http://www.g24i.com">http://www.g24i.com</a></td>
</tr>
<tr>
<td>Technology Used</td>
<td>Dye-sensitized solar cells (DSSC)</td>
</tr>
<tr>
<td>Big events (Part)</td>
<td>1. 2006: Got licenses from Konarka for DSSC</td>
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<td></td>
<td>2. 2007: Renewable Capital signed a licensing and joint development agreement with Konarka and, as planned, the agreement was then transferred to G24 Innovations</td>
</tr>
<tr>
<td></td>
<td>3. 2007: Signed agreement with BASF AG on DSSC</td>
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<td></td>
<td>4. 2007: the first company in the world to manufacture dye sensitised thin film solar cells</td>
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<td></td>
<td>5. 2008: In the UK, at the Business Commitment to the Environment (BCE) Environmental Leadership Awards, the Premier Product Award was won by G24 Innovations for its dye-sensitised thin-film solar cell technology</td>
</tr>
<tr>
<td>Description</td>
<td>The company has a production facility in Wales, and is targeting developing country users of it’s products. Production is at a 187,000 sq ft facility at Wentloog Park, Cardiff and plans to begin manufacturing early in 2007. G24i also works with Solarcoating Machinery GmbH for DSSC.</td>
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<tr>
<th>Name</th>
<th>Konarka Technologies, Inc.</th>
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<tr>
<td>URL</td>
<td><a href="http://www.konarka.com">http://www.konarka.com</a></td>
</tr>
<tr>
<td>Big events (part)</td>
<td>1. 2001: Konarka Technologies, Inc. founded as a spin-off from UMASS Lowell</td>
</tr>
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<td></td>
<td>2. 2002: Licensed dye-sensitized solar cell technology from EPFL</td>
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3. 2004: Chosen by the Defense Advanced Research Projects Agency to head a consortium of academic and national laboratories in the development of new materials for hybrid photovoltaics. Konarka managed the contract and shared the award of over $6 M with Arizona State University; the University of Massachusetts, Lowell; and the U.S. Army Soldier Systems Center, Natick, MA.
4. 2006: Licensed dye-cell technology to G24 Innovations of Cardiff, Wales
5. 2006: A $500,000 grant from the National Science Foundation (NSF). NSF Small Business Innovation Research (SBIR) Phase II project
6. 2006: Renewable Capital Ltd. in Licensing Agreement with Konarka for its Dye-Sensitized Solar Cell Technology for large-scale production
7. 2007: Konarka/NREL/University of Delaware team received $3.6 million award under the Department of Energy's Solar America Initiative
8. 2007: $750,000 SBIR Phase II award from US Air Force

Description
Konarka was established in 2001, and has a technology portfolio which incorporates the work of Nobel Laureate Alan Heeger on conducting polymers, and Sukant Tripathy’s work on photovoltaics.

<table>
<thead>
<tr>
<th>Name</th>
<th>Dyesol</th>
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<tr>
<td>URL</td>
<td><a href="http://www.dyesol.com/">http://www.dyesol.com/</a></td>
</tr>
<tr>
<td>Technology Used</td>
<td>Dye-sensitized solar cells (DSSC)</td>
</tr>
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<table>
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<tr>
<th>Big events (Part)</th>
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<tr>
<td>1. would be involved in a project with about 1.5 million euro investment in developing</td>
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<td>2. 2008: Timo Technology announced on 30 that it concluded a contract with Australia's Dyesol to establish dye-sensitized solar cell venture company. Dyesoltimo, venture company, plans to set 1 billion as establishment capital and through capital increase, capital will be expanded to 5 billion. The joint firm's strategy is to develop dye sensitized solar cell that can be mass-produced and commercialized it by the first half of this year. They are building dye sensitized solar cell production line in Korea.</td>
</tr>
<tr>
<td>3. 2009: Dyesol-Timo began a testing production of dye-sensitized solar cell (DSSC) which can generate power even in a cloudy day for the first time in the world.</td>
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<tr>
<td>4. Wholly owned subsidiary, Sustainable Technologies International Pty Ltd (STI), participant in the earliest commercial activates with EPFL.</td>
</tr>
<tr>
<td>5. Support “the International Conference on the Industrialisation of Dye Solar Cells” three times (most recently, April, 2009).</td>
</tr>
<tr>
<td>6. 2007: To exploit the European market, Dyesol Ltd. purchased Greatcell, locating Lausanne, close to EPFL. Greatcell enjoyed a rewarding and collaborative relationship with EPFL over a number of years, and this would be a big step in Dyesol’s move to become the leading player in Dye Solar Technology.</td>
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Appendix C  Ezra’s TDS
[We have cut this from the paper, but we note its significant contributions to innovation policy deliberations. We include here so the reviewers can see if they think it adds sufficiently to be put back in.]

Fig. C.1. The technology delivery system for solar innovation in private housing (based on Ezra, 1975)