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Highly uncertain dynamics of New and Emerging Science and Technologies pose special challenges to traditional forecasting tools. This paper explores the systematisation of the 'Forecasting Innovation Pathways' analytical approach through the application of Tech Mining. Once a set of multi-database, emerging technology search results has been obtained, we devise a means to help extract intelligence on key technology components and functions, major stakeholders, and potential applications. We present results pertaining to the development of dye-sensitised solar cells.

Keywords: Forecasting Innovation Pathways; New and Emerging Science and Technologies; Tech Mining; nanotechnology; dye-sensitised solar cells, technology intelligence

1. Introduction

New and Emerging Science and Technologies ('NESTs') are increasingly studied because of their potentially important 'emerging applications'. However, the highly uncertain dynamics of NESTs pose special challenges to traditional forecasting tools. Capturing and exploring multiple potential innovation pathways show considerable promise as a way of informing technology management and research policy. We have devised a 4-stage, 10-step approach to Forecast Innovation Pathways ('FIP'). This process integrates (a) heavily empirical 'Tech Mining' with (b) heavily expert-based multipath mapping. It combines a range of Future-Oriented Technology Analysis ('FTA') tools. These include innovation system modelling, text mining of Science, Technology & Innovation ('ST&I') information resources, trend analyses, actor analyses, and forecasting workshops.

This paper explores the systematisation of the FIP analytical approach through the application of Tech Mining. It presents results pertaining to the development of dye-sensitised solar cells (DSSCs). We treat DSSC abstract records through 2010 based on searches in four databases. We employ a set of multi-database NEST search results, sharing progress on our efforts to devise algorithms to help extract key technology components, significant actors, and potential applications.

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Our endeavours should be considered within the FTA context (see http://foresight.jrc.ec.europa.eu/). Over the years, FTA tools have expanded from technology forecasting of incrementally advancing technologies (e.g. consider Moore's law describing some six decades of continual advances in semiconductor capabilities) (Roper et al. 2011). Today, considerable interest is directed towards NESTs, as these are expected to create considerable wealth. NESTs tend to be less predictable than incremental innovation processes, as 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 endeavour to grapple with this challenging situation, we seek to provide usable intelligence on the developmental trajectory of a target NEST and also on the pertinent contextual forces and factors affecting that. Such technology opportunities analysis (Porter et al. 1994) for NESTs poses notable challenges. FTA increasingly includes science-based technologies, with less orderly developmental trajectories (cf. 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 (Porter 2010) and applying it to serve technology policy or management ends (Scapolo, Porter, and Rader 2008).

Recently, Robinson (Robinson et al. 2011) has introduced the approach of 'FIP'. That paper provides conceptual background for the endeavour of combining 'Tech Mining' (Porter and Cunningham 2005) and 'multipath mapping' (Robinson and Propp 2008). It explores the promise of this approach through its application to two illustrative innovation situations: nanobiosensors and 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 – 'DSSCs'.

Anticipating innovation pathways can assist R&D managers as they set priorities, new product managers as they compose development teams, and national policy-makers as they formulate infrastructures to encourage innovation.

2. Background

2.1. *Tech Mining and FTAs*

Bibliometrics – counting activity levels and identifying patterns in R&D bibliographic records, plus patent analyses – has contributed to science and technology studies for decades (cf. Van Raan 1988). With the expansion of databases that compile abstract records and of desktop computing power, text mining of these records further enriches the empirical base. Tech Mining (Porter and Cunningham 2005) is our shorthand for such activities.

'Research profiling' (Porter, Kongthon, and Lu 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 has already been heavily researched and 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 of compiling this intelligence on a given NEST regarding the development pathway (i.e. to reach beyond R&D). Here, we go further to apply text mining tools (see www.theVantagePoint.com) to such compilations of research article and patent abstracts. We work to uncover developmental trends and to compile mentions of possible applications and developmental or impact issues. We also identify active organisations and work to relate the content of the data searches to particular innovation process trajectories.

2.2. *Analysing NESTs*

NESTs comprise a loose category (Foxon et al. 2005; Robinson and Propp 2008). Classical technology forecasting methods were devised to address incrementally advancing technological systems. These 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 for incorporating science-based advances (e.g. biotechnologies and nanotechnologies), and these 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' (Coates 1976) societal consequences. We seek to contribute to the development of analytical tools to relate early-stage scientific advances to long-term implications (i.e. potential applications).

2.3. *Innovation system conceptual modelling*

A variety of approaches aim to capture the systemic processes by which emerging technologies contribute to commercial innovation. To facilitate the analysis of technological change, Hekkert et al. (2007) articulate 'functions of innovation systems'. Some researchers look into what kind of innovation transfer is most effective (e.g. Liu, Tang, and Zhu 2008; O'Shea, Chugh, and Allen 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 conceptual modelling 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 the development and diffusion of sustainable technologies (Jacobsson and Johnson 2000; Foxon et al. 2005; Markard 2006).

Among the various approaches to capture the essentials of innovation systems, the technology delivery system ('TDS') has demonstrated enduring value by capturing and representing (1) key enterprise (to 'deliver' an innovation) and (2) contextual factors (impinging on such delivery). In our paper, the concept of TDS recognises the inherent uncertainties of innovation pathways. Ezra (1975) offered a TDS to help explain why solar energy innovation in residential housing applications was not notably successful. Wenk and Kuehn (1977) advance TDS as a form of socio-technical system conceptual modelling 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. commercialisation). Our TDS considers enterprise elements needed to effect innovation and it points out influential factors in the immediate nanobiosensor environment. We seek key leverage points at which the innovation pathways can be strongly influenced.

The elements that appear in a TDS depiction change from application to application. For instance, Shi, Porter, and Rossini (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 commercialisation. Roper et al. (2011) elaborate on a means to formulate a TDS for a given NEST – the approach is qualitative and might be called heuristic. It draws upon the literature and available human knowledge of the particular innovation system, within the context of a more general innovation context (i.e. the socio-economic context in which a potential application is being promoted).

3. Framework and data

3.1. *Framework*

The FIP framework includes four stages, broken down into 10 steps (Figure 1).

We label Steps A–J, but emphasise that FIP is not a once-through, linear process. Rather, this method gathers information pursuant to the various steps, quite willing to revisit the 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 – alongside to call attention to the desirability of ongoing involvement of various knowledgeable persons.

Stage 1 is largely descriptive. It seeks to gain basic understanding of the technology – how it works and what functions it can accomplish (Step A). In addition, we work to characterise the organisational and contextual factors involved in developing and applying this technology (Step B). As discussed earlier, we favour TDS modelling to do this compactly and informatively.

Stage 2, in contrast, is heavily empirical. We search for R&D activity in suitable 'ST&I' databases and profile that activity and the associated actors from these data (Steps C and D). Many analytical tools can serve to profile R&D, including bibliometric analyses, social network analyses, and trend analyses. We adapt these to facilitate our study as a function of the state of development of NESTs. We seek innovation indicators (i.e. empirical measures to gauge technological maturation and prospects for successful applications). We also seek to determine how technological characteristics link to functional advantages, applications, and potential users (Step E).

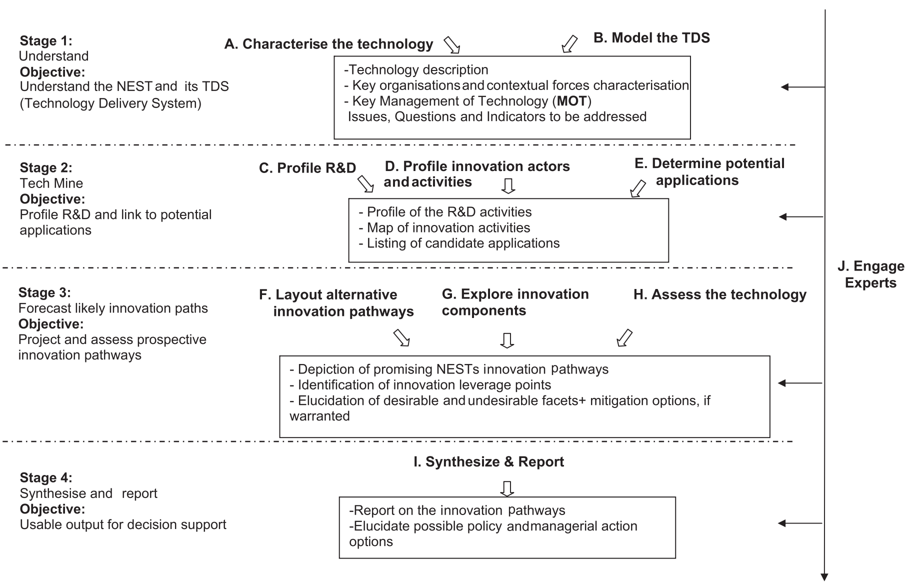

Figure 1. Framework for forecasting NEST innovation pathways.

Step J, engaging experts, is an iterative process. In our FIP exercises to date, expert engagement has tended towards informal, in-depth involvement of a limited number of knowledgeable individuals (plus a workshop, discussed later). We distinguish that from formalised involvement of many experts (e.g. Delphi procedures), although one could consider augmenting the FIP approach by such techniques.[1] Two different situations can be contrasted. In one, technical experts who know the NEST intimately reach out to understand and characterise its innovation processes. In the other (our case), the analysts are conversant with the FTA, Competitive Technical Intelligence, and innovation processes, but lack in-depth knowledge of the NEST itself. Accordingly, we need technical guidance. (The degree of such needs varies with the complexity of the NEST.) At Georgia Tech, we drew upon two faculty members to orient our work. Most importantly, we found a willing PhD student (Chen Xu) to collaborate in our analyses. Early formulation of the TDS with pointers towards key institutions can help illuminate needs for special expertise. Eliciting advice from such experts may, then, lead to the identification of additional (or different) key players in the TDS.

Stage 3 brings expertise to bear on the system depiction (Stage 1) and empirical results from Stage 2. Step F digests prior results to present those to participating experts and stakeholders (Step G). Convening a workshop with multiple perspectives can anchor Step G – exploration of alternative innovation pathways. This is meant to be a creative endeavour to identify potential applications and draw up different ways of attaining these.

Work in this stage should take into account competing technologies that may 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 important hurdles must be surmounted along the various innovation pathways? What key policy and/or business management leverage points enhance the prospects of success? If possible, it can also be valuable to obtain the views of the participants on impact assessment: what are the potential effects that could arise from pursuing a given development path?

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

3.2. *The case of DSSCs*

Nanotechnology entails engineering matter at molecular scale, seeking novel applications of new materials and devices. Within the context of ongoing empirical analyses of nanotechnology (‘nano’) R&D, we focus here on how nanomaterials are being used to enhance the performance of solar cells, an important renewable energy technology form (also known as photovoltaics). DSSCs, one type of nano-enabled solar cells with special promise, are made of low-cost materials and are less equipment intensive than other solar cell technologies.

3.3. *Data*

We chose a modular, Boolean term search approach (Porter et al. 2007) to identify DSSC-related activity in four databases: Web of Science (WOS), EI Compendex, Derwent World Patent Index (DWPI), and Factiva. First, we generated direct DSSC technical terms. This showed high precision (minimal noise). Second, we enriched these search terms according to different expressions of DSSCs and closely related technical structures to increase recall. Third, we removed duplicates with the first search. We then added limitations – such as restricting to DWPI records that also appear in certain International Patent Classifications. We added exclusion terms for the publication databases. We tested the performance of the search modules. We created search algorithms somewhat tailored for each of the four databases (details in Appendix 1). Data-cleaning in VantagePoint software (Porter et al. 2007) refined the data downloaded from the four databases. This analysis treats DSSC abstract records through 2010 based on these searches:

- 4104 documents (including 3134 articles) appearing in the Science Citation Index (SCI) of WOS (fundamental research emphasis);[2]
- 3730 documents from EI Compendex (journal and conference articles);
- 3097 patent families from DWPI; and
- 2771 documents from Factiva (treating a range of press releases, trade publication items, etc.)

4. Results

We emphasise the relatively novel steps in our 10-step FIP process (Figure 1) for the DSSC case:

- developing a TDS model (Step B);
- eliciting information on stakeholders and potential applications from text mining (Steps D and E); and
- consolidating empirical and expert knowledge to lay out candidate innovation paths (Steps F and G, with J).

Detailing how the solar cells function (Step A) is treated only briefly (Appendix 2). DSSC R&D (Step C) profiling outputs are selectively illustrated. Technology assessment (Step H) has not been carried out yet. Synthesis and reporting (Step I) to explicit target users have not been emphasised in this scholarly exercise. The primary aim is to convey the method, with a secondary interest in the DSSC characterisation.

4.1. *Compose TDS (Step B)*

The TDS approach is akin to other technology innovation system approaches, as noted, but we favour its distinct treatment of (1) the enterprise (organisations with requisite capabilities) to develop the innovation and take it to market and (2) the key contextual factors (actors, trends, and events) affecting the success of that innovation process. Clear understanding of both sets of factors offers a valuable decision aid to inform successful NEST management. Our TDS considers enterprises pursuing DSSC innovations, and it points out influential factors in the immediate solar cell development environment. We seek key leverage points at which the innovation pathways can be strongly influenced.

Figure 2 presents our TDS, targeted at the USA – we chose this national focus to focus on a set of key actors. In terms of the enterprises to accomplish commercial innovation based on DSSC technology, we sketch three loose groups of companies. We note relatively few of those companies 'doing it all' – that is, publicly researching, patenting, and openly pursuing business opportunities. Figure 2 also shows notable governmental and competitive factors. The recent upsurge in support for renewable energy promotes solar cell initiatives. In the long term, we believe that general

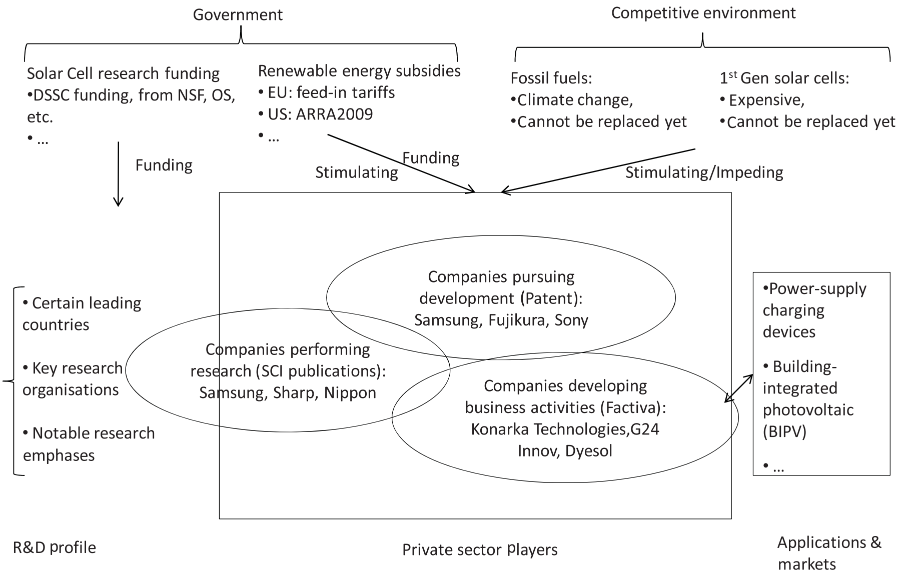

Figure 2. TDS for DSSCs in the USA.

economic forces will favour 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.

We developed this initial DSSC TDS by mining our database search results for leads on important stakeholders and influential environmental factors (e.g. economy recovery act support for renewable energy development). Key review articles helped us to understand the important components and players in this 'delivery system'. Engagement of our collaborating solar cell researchers helped distinguish the more important elements. Review of the TDS by several knowledgeable persons helped tune this simple conceptualisation.

4.2. *Profile R&D (Step C)*

This activity draws heavily on bibliometric and text mining analyses of the database search results. 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 subtechnologies (i.e. those appearing much more frequently in the most recent time period). Extracting the organisational entities – particularly those publishing R&D articles, those patenting, and those discussed in the business-oriented literature – identifies possibly important actors in the DSSC arena. Mapping research networks identifies collaborations. To provide a sense of this, we focus selectively as such analyses are fairly well known (Porter, Kongthon, and Lu 2002).

We begin by showing trends based on the annual activity from each database in Figure 3. It is clear that the research publications drawn from the SCI and Compendex databases keep growing and show similar trends. This suggests that fundamental research on DSSC continues to increase essentially exponentially. The data from both DWPI and Factiva show a small peak in 2005 and suddenly decrease in 2006. Actually, the data from Compendex also grow slower in 2006. We are

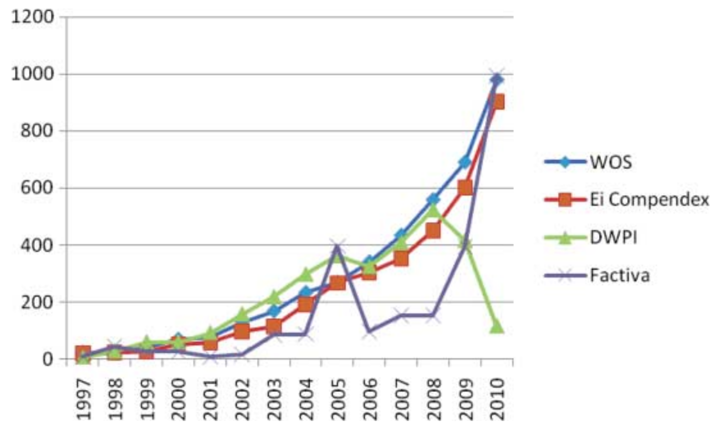

Figure 3. DSSC publication and patent trends.

not sure why this is so; we observe that the Japanese government did cancel solar energy subsidies in 2006. After 2006, DWPI patents resume growth, although the data in 2009 and 2010 were not completely collected by Thomson Reuters at the time of the downloading. After 2008, the Factiva records suddenly climb quicker than the activity in the other databases does. The rapid growth of DWPI and Factiva data suggests that DSSC technology is becoming more mature and is possibly entering into an era of rapid commercialisation.

We applied science overlay mapping (Leydesdorff and Rafols 2009) to locate DSSC R&D among the disciplines. This approach uses the Subject Categories assigned to journals by WOS. Accordingly, for a set of publications indexed by WOS (in this case, by SCI, which is part of WOS), we located this research via the journals in which it appears. Figure 4 builds on a base map reflecting the 175 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 WOS (Porter and Raflos 2009). These 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 locates the DSSC publications based on the journals in which they appear overlaid on a base map of science.[3] This illustrates that global DSSC research involves an extensive range of research fields concentrated in the Materials Science and Chemistry macro-disciplines. This analysis contributes to an understanding of the fields involved, which is necessary to identify technical experts. We can also locate research concentrations geographically by overlaying indications on anything from a world map to a regional one (not shown).

4.3. *Profile innovation actors and activities (Step D)*

Since 2009, WOS has been providing a funding acknowledgement field as it indexes publications. This can indicate key funding agencies for a NEST under study (potentially important in the TDS). For DSSCs, the results are quite surprising. The US National Science Foundation (NSF) shows forth on 42 of 1691 publications since 2009. The Swiss NSF accounts for 35 of some 41 papers with Swiss funding; Swedish funding similarly shows up for 42 papers, led by the Swedish Energy Agency. But the dominant funding source is NSFC (China) with 216 papers acknowledging its support.

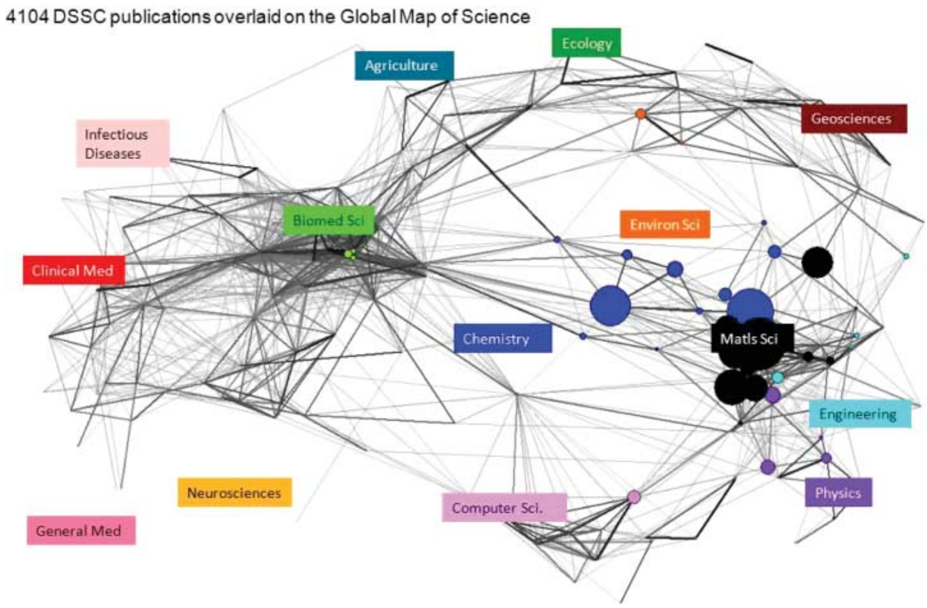

Figure 4. DSSC science overlay map.

Based on the SCI data set, we identified the top 11 research publishing institutions (Table 1) and also examined how heavily cited their publications are. Especially notable leaders are

- Swiss Federal Institute of Technology, Lausanne (also appearing as EPFL – École Polytechnique Fédérale de Lausanne, Lausanne), dominates with 24,100 cites (five times the count of any other, without doing extensive data-cleaning);
- US National Renewable Energy Lab (NREL) is second with 4780, but much reduced activity recently;
- several institutions have over 3000 citations: the Chinese Academy of Sciences (CAS), the National Institute of Advanced Industrial Science & Technology (AIST – Japan), Uppsala University (Sweden), and Imperial College of Science, Technology & Medicine (the University of London);
- National Taiwan University lags with 817, followed by the Korean Institute of Science & Technology with 1013 cites; and
- three others have 1330 to 1717 cites (to their many publications).

Table 1 partitions publication and citation shares of these 11 top institutions for (1) the period extending through 2008 and (2) that since then (2009–2011, with 2011 incomplete). The Swiss Federal Institute of Technology is certainly the dominant single institution researching DSSCs.[4] Especially in recent years, the multi-institute CAS has also been a dominant player. Since 2009, EPFL has published 21 papers that have already received 10 or more cites; CAS, 12 such papers; and AIST, only 4. Examination of the research emphases of such leading players can provide intelligence on where the field is heading. Our initial examination of these recent, highly cited papers did not discern particular foci.

Table 1. Leading DSSC research institutions (showing percentages within these 11 organisations).

	Cites share through 2008 (%)	Cites share 2009 onwards (%)	Pubs share through 2008 (%)	Pubs share 2009 onwards (%)
CAS	6.0	19.9	19.5	25.3
Swiss Federal Institute of Technology (EPFL)	49.3	28.6	20.5	18.5
AIST (Japan)	7.7	4.4	11.1	7.2
Uppsala University	8.1	4.7	5.7	9.5
Korean Institute of Science & Technology	1.9	5.1	6.3	8.2
Korea University	2.3	10.3	6.1	8.2
National Taiwan University	1.5	5.2	5.8	7.2
Imperial College, London	6.9	6.9	6.2	6.4
Royal Institute of Technology	3.0	8.0	6.8	4.5
Kyoto University	3.3	5.5	5.8	3.5
NREL (USA)	10.0	1.2	6.1	1.4

Table 2. Leading DSSC companies' prevalence in various data sources.

	SCI	EI	DWPI	Factiva
Samsung SDI Co. Ltd	52*	38	65*	4
Sharp Co. Ltd	27*	24	17*	4
Nippon Oil Corp	15*	35	27*	10*
Hayashibara Biochem Labs Inc.	14*	9	0	0
Fujikura Ltd	12*	8	17*	9*
Chemicrea Co. Ltd	10*	8	0	0
Sumitomo Osaka Cement Co. Ltd	10*	3	3	2
Toshiba Co. Ltd	9*	7	2	1
Konarka Technologies Inc.	7*	11	11*	9*
Dong Jin Semichem Co. Ltd	0	1	16*	8*
Sony Corp.	10	10	17*	17*
Evonik Degussa GmbH	0	0	0	15*
STMicroelectronics NV	0	0	0	12*
Data Systems & Software Inc.	0	0	0	8*
Dongjin Semichem Co. Ltd	0	1	0	8*
Dyesol Ltd	3	3	2	8*

*Indicates the advantages of each corporation.

We especially attended to industrial players, identifying the leading organisations active in each of the different data sources. Table 2 compares selected organisations in this way.[5] Note the variation in prominence across these data sets. For instance, Samsung is the leading patentee and publisher (in this compilation) on DSSCs, but has not been frequently mentioned in conjunction with business actions (Factiva database). Dainippon Printing is extremely active in patent families but does not publish. The use of multiple information sources in conjunction with each other enriches perspective on how the NEST is being developed.

Once such highly active players have been identified, an especially useful analytical step is to profile their R&D and business activity in detail. Using VantagePoint and MS Excel, one can generate 'breakout tables' quickly. Depending on one's foci, these might detail for, say, the leading patent assignee companies (not shown here) in terms of

- country of origin;
- most active International Patent Classes;
- % of their patents in the most recent years;
- leading inventor teams; and
- notable collaborators.

Research profiling can extend to the country level. SCI tallies since 2009 have found China to be dominant with 440 papers including at least one Chinese author. The next six countries are South Korea (267), Japan (192), Taiwan (181), the USA (167), Switzerland (101), and India (81). Using R&D publication, patents, and business activity compilations, one can enable social network analyses within and among organisations.

4.4. *Determine potential applications (Step E)*

We introduced a new technique called 'cross-charting' to explore the links from technological attributes (e.g. particular nanomaterials or nanostructures and particular technical advances) – to functional advantages that these offer – to potential applications, in particular markets; that is, cross-charting can suggest ways that particular technologies might link to potential applications. The content of a given cross-chart will vary depending on one's interests. 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 be generally advantageous instead.

Figure 5 presents a follow-on cross-chart to illustrate focus on a particular target market – glass-walled building structures (especially greenhouses). We worked our way back from that intended innovation to identifying particular attributes that could contribute importantly to it (e.g. light-transmitting solar cells). We continued upstream to direct attention to features, solar cell types, and advantageous nanomaterials. The idea is that this helps focus monitoring efforts to seek out advances that could facilitate our desired application. Conversely, we would direct less attention to other nanomaterials and solar cell types that offer less potential gain for our target application.

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 'use' fields within DWPI reveals some 19 patent families, of which Samsung holds 6. Next research steps might include visiting Samsung's websites and initiating direct discussion with their inventors. Alternatively, other cross-chart foci are quite possible. Were our interests centred on a given technical aspect (e.g. pursuit of organic-metallic dyes), we could make a different cross-chart that accentuates relationships with their special capabilities. This could help us to identify potential partners with complementary interests at different places along this technology development progression, thereby serving 'Open Innovation' purposes (Chesbrough 2006).

In this paper and in companion analyses of nanobiosensors, we found value in

- subdividing the technical elements (e.g. distinguishing among various nanostructured materials);

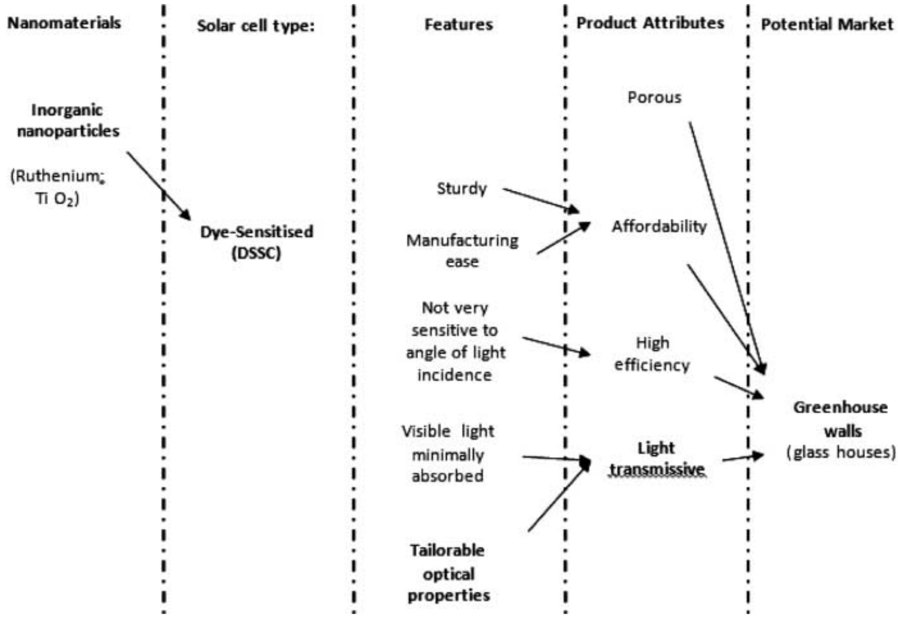

Figure 5. Focused DSSC cross-charting: tracking materials to technology to functions to applications.

- engaging with those knowledgeable about the technology through the process of further specifying the set of important, and distinctive, functions;
- exploring which functions pertain to particular applications (in some cases requiring partitioning functions and/or application sets); and
- considering links between applications and commercial opportunities (users, sectors, etc.).

4.5. *Lay out alternative innovation pathway (Step F, with Step J)*

This stage was completed in two rounds. First, we read overview papers, executed an initial database search, and text mined the database search results. We carried out preliminary searches to identify local expertise to help guide us. We also contacted Georgia Tech and Emory University colleagues with a background in solar cells. One professor invited us to meet him. The face-to-face interview with him provided input to allow a first evaluation of our analyses. With a doctoral student's cooperation, we continued our analyses to FIP.

A second round of contacts focused on identifying workshop participants. Again, our collaborating material science doctoral student helped the social science organisers identify and encourage participation by two professors and four doctoral students with expertise in nanomaterials, organic solar cells, and silicon solar cells. In addition, a faculty member with expertise in innovation processes and nanotechnology joined the three of us (Guo, Huang, and Porter) in the workshop, for a total of 10 persons. This focused on mapping likely innovation avenues, following the process described and demonstrated by Robinson and Propp (2008). Their expert workshops involve a wider spectrum of experts and stakeholders for a more extended interaction (e.g. full day). Our collaborating expert helped interpret results from the workshop (which entailed abundant note-taking).

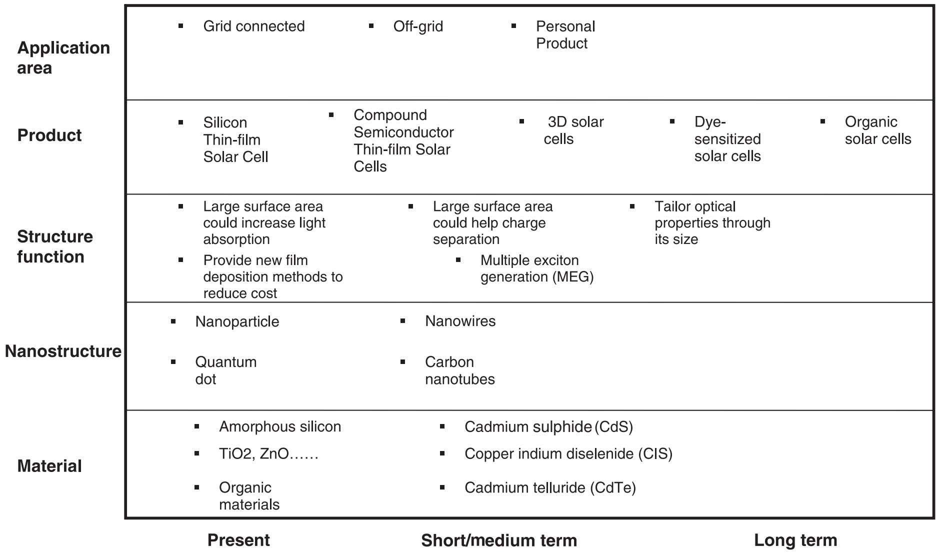

Figure 6. Ingredients for the multipath exploration.

Figure 6 shows an introductory slide to initiate the workshop process. It presents some key elements that we established in our desk research, tuned through expert interviews. The presentation aims 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 demonstrate when one might expect these elements to be highly functional. This provides a framework for discussion and rapid feedback. Such visualisations stimulate workshop interactions and create a framework for drawing out the intelligence held by the experts in the workshop, a scaffold upon which to locate their knowledge.

Figure 7 presents a post-workshop depiction of main alternative development pathways. Doug Robinson crafted this (Porter et al. 2010).

4.6. *Explore innovation components (Step G)*

Figure 7 provides the framework to explore sensitivities and options. Potential innovation pathways can be reshaped; key promising technologies can be identified and positioned in a time frame; and obstacles and opportunities that will facilitate or inhibit progress along a particular pathway can be located. In particular, the map flags potential managerial and/or policy issues that need to be addressed early in development (e.g. scalability of DSSC production). Once complete, such a multipath map can be updated, monitored, and circulated to the experts in the workshop (and others) for verification and expansion. Such visualisation of a pathway can play a central role in exploring innovation routes for a potentially disruptive NEST, when the future is open ended and thus an evolving map is needed. Presentations of alternative development scenarios to interested parties can communicate and advance foresight processes (Step I).

FIP can identify lead and lag relationships between DSSCs and other solar cells, such as those that are silicon based or quantum dot enhanced. Laying out possible development pathways can help figure out which point towards more special applications (higher price) or niche markets.

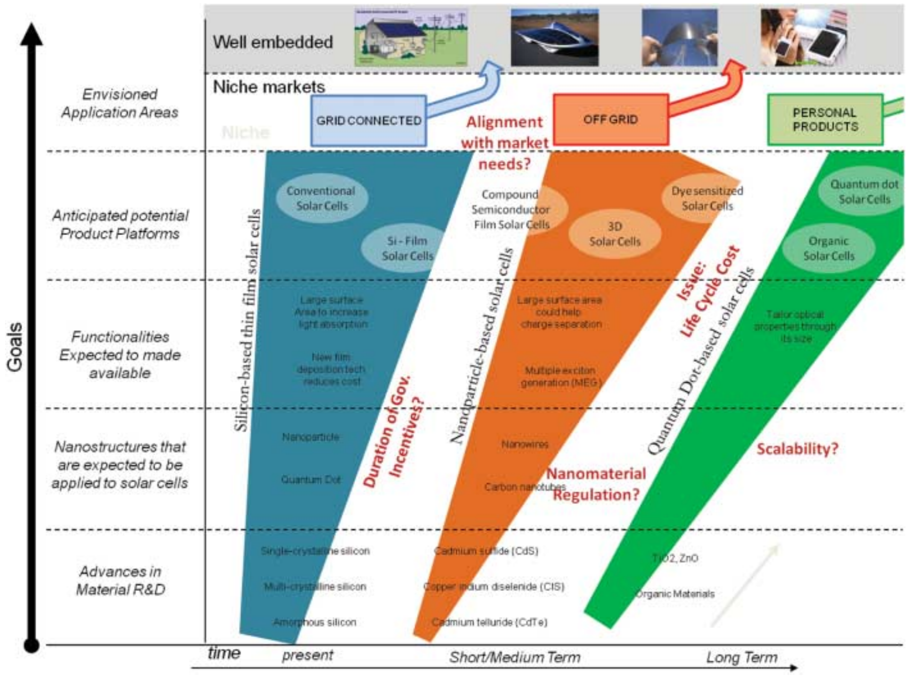

Figure 7. Multipath map for DSSCs.

The silicon lead could prove tough competition for those pursuing DSSC applications (much as the immense silicon infrastructure has become the dominant semiconductor platform).

Figure 7 is obviously a highly simplified schematic. One can consider what is involved in progressing along a given pathway to particular products, processes, or services – offered to particular markets. Such an exploration should identify essential requirements for success that are not yet available. The process should also explore 'how' these could be brought about. For instance, does a particular need call for government funding or standard setting? Do any requisite developments call for partnering among certain organisations (and, if so, which)? Figure 7 details a few issues (as an illustration), but a full map would show critical issues that would need to be handled for particular application targets. For instance, what are the full life-cycle costs for a given solar cell formulation?

4.7. *Calls to perform technology assessment (Step H)*

Much of the FIP process serves to promote the first type of technology assessment – evaluation of competing technologies. From Figure 1 onwards, we are oriented towards the consideration of the target NEST with full awareness that it does not enter a vacuum – it does not 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, to expand selection criteria beyond technical functionality to consider cost, infrastructures, and compatibility.

This leads us to the second type of technology assessment – impact assessment. We especially would like to identify potential hazards and side effects, including environmental, health, and safety concerns that could arise (cf. www.iaia.org). Figure 7 raises the desirability of life-cycle analyses to consider likely life span, maintainability, material transformation (e.g. due to outside exposure over many years), and eventual recycling and disposal means.

Of note, when we compared topical concentrations in the SCI DSSC publications between 2005–2007 and 2010–2011, publications in environmental journals increased dramatically from 2 to 29, suggesting small, but growing, attention to such facets. 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 fit within the risk and regulation landscape? Are the protocols for handling such substances in place? Is the risk framework adequate? The innovation pathways call attention to a need to address such issues that could affect DSSC development and applications.

5. Discussion and future prospects

We have worked at FIP for several NESTs, including nanobiosensors (Huang et al. 2010), deep brain stimulation (Robinson et al. 2011), and NESCs (Guo, Huang, and Porter 2010). This paper pursues FTA pertaining to the development of DSSCs.

DSSCs reflect a variety of component technologies, with R&D emphases distributed among them. In one stream of exploration, we consider the intersection of advanced dye formulations (to enhance light energy capture) and semiconductor material advances (to improve conversion to usable electrical energy). Sorting technical terms is challenging but benefits from expert inputs. Such details can enrich cross-charting procedures to elucidate which key players (countries and institutions) currently pursue which priorities. This, in turn, should help array strong candidate innovation pathways. We are investigating DSSC technical component developments through patent analyses that combine text mining, semantic/syntactic analyses, and problem-solving algorithms such as TRIZ (the Theory of Inventive Problem Solving; cf. Rantanen and Domb 2002) to help locate current capabilities along innovation pathways.

This paper extends our FIP approach. Earlier papers have suggested how particular FTA techniques can contribute to the FIP steps. We illustrate the use of multiple information resources in conjunction with expert opinion to inform FIP, with special attention to the experiences in devising a TDS model and conducting a forecasting workshop.

Our FIP approach, which combines qualitative and quantitative tools in the 'Profile, Project and Assess' steps, has strengths and shortcomings. It is effective in identifying the first-round potential innovation pathways and then zooming into these through augmented expert engagement exercises. The richness of the data is unquestionable, but labour intensive. The FIP approach is a work in progress. Experience in applying it to several NEST cases indicates good potential, but also limitations. The potential draws on the practical combination of empirical and expert knowledge to capture key technology and contextual attributes, affecting the prospects for effective applications. Drawing attention to innovation pathways (e.g. Figure 7) stimulates thinking about factors affecting these, which in turn can trigger consideration about research, technology management, and policy options. Laying out alternative pathways also raises impact assessment needs. Figure 7 notes possible impacts and issues worth further analyses. The variability among NEST situations and possible decision needs calls for the FIP approach to be considered very flexibly. The amount of available data, time horizons for innovation, and scope of study all reinforce the need to adapt these 10 steps to one's priorities. Figure 7 provides a stimulating visualisation of potential innovation pathways, but it also obviously simplifies complex interactions and should not be taken as a projection.

FIP aims to inform ST&I management (private sector) and policy (public sector). We are yet to evaluate whether outputs, such as those presented here, will prove useful in these venues. We recognise that Step I (synthesise and report) is not automatic. We believe that a well-chosen mix of visual representations with charts and text will need to be crafted to the preferences of target users (Porter and Cunningham 2005).

Notes

1. 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 generalisable.
2. See Appendix 1 for WOS search term.
3. These science overlay maps have been described elsewhere (Leydesdorff and Rafols 2009; Porter and Rafols 2009; Rafols and Meyer 2010; Rafols, Porter, and Leydesdorff 2010). The base map used here reflects SCI journal cross-citation in 2007, aggregated into 175 Subject Categories. Based on factor analysis, these are grouped into macro-disciplines (the labels shown in Figure 4). For more information, or to make your own science overlay maps, visit www.interdisciplinaryscience.net or www.idr.gatech.edu/.
4. DSSCs were first reported there in a hugely cited 1991 article (O'Regan and Gratzel 1991); Gratzel and colleagues continue to lead the field.
5. Table 2 does not include the full updated information through 2009 and 2010.

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References

Cagnin, C., M. Keenan, R. Honston, F. Scapolo, and R. Barré, eds. 2008. *Future-oriented technology analysis: Strategic intelligence for an innovation economy*. Berlin, Heidelberg: Springer-Verlag.

Chesbrough, H.W. 2006. Open innovation: A new paradigm for understanding industrial innovation. In *Open innovation: Researching a new paradigm*, ed. H.W. Chesbrough, W. Vanhaverbeke, and J. West, 109–20. Oxford: Oxford University Press.

Coates, J.F. 1976. Technology assessment: A tool kit. *Chemtech* 6 (June): 372–83.

Collingridge, D. 1980. *The social control of technology*. London: Pinter.

Ezra, A.A. 1975. Technology utilization: Incentives and solar energy. *Science* 187: 707–13.

Foxon, T.J., R. Gross, A. Chase, J. Howes, A. Arnall, and D. Anderson. 2005. UK innovation systems for new and renewable energy technologies: Drivers, barriers and systems failures. *Energy Policy* 33, no. 16: 2123–38.

Guo, Y., L. Huang, and A.L. Porter. 2010. The research profiling method applied to nano-enhanced, thin-film solar cells. *R&D Management* 40, no. 2: 195–208.

Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits. 2007. Functions of innovation systems: A new approach for analyzing technological change. *Technological Forecasting & Social Change* 74, no. 4: 413–32.

Huang, L., Z.C. Peng, Y. Guo, and A.L. Porter. 2010. Identifying the emerging roles of nanoparticles in biosensors. *Journal of Business Chemistry* 7, no. 1: 15–30.

Jacobsson, S. and A. Johnson. 2000. The diffusion of renewable energy technology: An analytical framework and key issues for research. *Energy Policy* 28, no. 9: 625–41.

Leydesdorff, L., and I. Rafols. 2009. A global map of science based on the ISI subject categories. *Journal of the American Society for Information Science and Technology* 60, no. 2: 348–62.

Liu, B., N. Tang, and X. Zhu. 2008. Transferring technology across borders: Institutional effects in Chinese context. *The Journal of Technology Transfer* 33, no. 6: 619–30.

Markard, J. 2006. Technological innovation systems and the multi-level perspective: Towards a combined framework for the analysis of innovation processes. Understanding processes in sustainable innovation journeys, Utrecht.

van Merkerk, R.O., and H. van Lente. 2005. Tracing emerging irreversibilities in emerging technologies: The case of nanotubes. *Technological Forecasting & Social Change* 72, no. 9: 1094–112.

O'Regan, B., and M. Gratzel. 1991. A low-cost, high-efficiency solar-cell based on dye-sensitized colloidal TiO_2 films. *Nature* 353, no. 6346: 737–40.

O'Shea, R.P., H. Chugh, and T.J. Allen. 2008. Determinants and consequences of university spinoff activity: A conceptual framework. *The Journal of Technology Transfer* 33, no. 6: 653–66.

Porter, A.L. 2010. Technology foresight: Types and methods. *International Journal of Foresight and Innovation Policy* 6, nos. 1/2/3: 36–45.

Porter, A.L., and S.W. Cunningham. 2005. *Tech mining: Exploiting new technologies for competitiveadvantage*. New York: Wiley.

Porter, A.L., Y. Guo, L. Huang, and D.K.R Robinson. 2010. Forecasting innovation pathways: The case of nano-enhanced solar cells. ITICTI – International Conference on Technological Innovation and Competitive Technical Intelligence, Beijing.

Porter, A.L., X.-Y. Jin, J.E. Gilmour, S. Cunningham, H. Xu, C. Stanard, and L. Wang. 1994. Technology opportunities analysis: Integrating technology monitoring, forecasting & assessment with strategic planning. *SRA Journal (Society of Research Administrators)* 26, no. 2: 21–31.

Porter, A.L., A. Kongthon, and J.-C. Lu. 2002. Research profiling: Improving the literature review. *Scientometrics* 53, no. 3: 351–70.

Porter, A.L., and I. Rafols. 2009. Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. S*cientometrics* 81, no. 3: 719–45.

Porter, A.L., J. Youtie, P. Shapira, and D. Schoeneck. 2007. Refining search terms for nanotechnology. *Journal of Nanoparticle Research* 10, no. 5: 715–30.

Rafols, I., and M. Meyer. 2010. Diversity and network coherence as indicators of interdisciplinarity: Case studies in bionanoscience. *Scientometrics* 82, no. 2: 263–87.

Rafols, I., A.L. Porter, and L. Leydesdorff. 2010. Science overlay maps: A new tool for research policy and library management. *Journal of the American Society for Information Science & Technology* 61, no. 9: 1871–87.

Rantanen, K., and E. Domb. 2002. *Simplified TRIZ: New problem-solving applications for engineers and manufacturing professionals*. Boca Raton, FL: CRC Press.

Robinson, D.K.R., L. Huang, Y. Guo, and A.L. Porter. 2011. Forecasting innovation pathways for new and emerging science & technologies. *Technological Forecasting & Social Change*, doi:10.1016/j.techfore.2011.06.004.

Robinson, D.K.R., and T. Propp. 2008. Multi-path mapping for alignment strategies in emerging science and technologies. *Technological Forecasting & Social Change* 75, no. 4: 517–38.

Roper, A.T., S.W. Cunningham, A.L. Porter, T.W. Mason, F.A. Rossini, and J. Banks. 2011. *Forecasting and management of technology*. 2nd ed. New York: John Wiley.

Shi, H., A.L. Porter, and F.A. Rossini. 1985. Microcomputers in developing countries: Industrialization in the information age. *International Journal of Applied Engineering Education* 1, no. 5: 321–8.

Scapolo, F., A.L. Porter, and M. Rader. 2008. Introduction to special issues: Future-oriented technology analysis (FTA): Impact on policy and decision making. *Technological Forecasting & Social Change* 75, no. 4: 457–61.

Technology Futures Analysis Methods Working Group (Alan L. Porter, Brad Ashton, Guenter Clar, Joseph F. Coates, Kerstin Cuhls, Scott W. Cunningham, Ken Ducatel, Patrick van der Duin, Luke Georghiou, Ted Gordon, Hal Linstone, Vincent Marchau, Gilda Massari, Ian Miles, Mary Mogee, Ahti Salo, Fabiana Scapolo, Ruud Smits, and Wil Thissen).

2004. Technology futures analysis: Toward integration of the field and new methods. *Technological Forecasting and Social Change* 71, no. 1: 287–303.
Van Raan, A.F.J., ed. 1988. *Handbook of quantitative studies of science & technology*. Dordrecht: North Holland. http://www.cwts.nl/.
Wenk, E., and T.J. Kuehn. 1977. Interinstitutional networks in technological delivery systems. In *Science and technology policy*, ed. J. Haberer, 153–75. Lexington: Lexington Books.

Appendix 1. WOS DSSC search terms

No.	Records	Term	Annotation
#1	4000	TS = (((dye-sensiti*) or (dye* same sensiti*) or (pigment-sensiti*) or (pigment same sensiti*) or (dye* same sense)) same (((solar or Photovoltaic or photoelectr* or (photo-electr*)) same (cell or cells or batter* or pool*)) or photocell* or (solar-cell*)))	Various expressions of DSSCs (pigment-sensitised solar cell is a kind of DSSC)
#2	1204	TS = ((DSSC or DSSCs) not ((diffuse cutaneous systemic sclerosis) or (diffuse cutaneous SSc) or (diffuse SSc) or (distributed switch and stay combining) or (Distributed Static Series Compensator*) or (decoupled solid state controller*) or (Active Diffuse Scleroderma*) or (systemic sclerosis) or (diffuse scleroderma) or (Deep Space Station Controller) or (Data Storage Systems Center) or(decompressive stress strain curve) or (double-sideband-suppressed carrier) or (Flexible AC Transmission Systems) or (DSS-induced chronic colitis) or (Dynamic Slow-start) or (dextran sulphate sodium) or (disease or patient* or QSRR)))	Seeking papers that include (1) relate to DSSCs and exclude (2) noisy data
#3	330	TS = ((((dye-Photosensiti*) or (dye same Photosensiti*) or (pigment-Photosensiti*) or (pigment same Photosensiti*)) same ((solar or Photovoltaic or photoelectr* or (photo-electr*)) same (cell or cells or batter* or pool*))) not (melanocyte* or cancer))	(1) Various expressions of DSSCs or photo-sensitised solar cells; using (2) (melanocyte* or cancer) to exclude noisy data
#4	188	TS = (((((dye adj (sensiti* or photosensiti*)) and (conduct* or semiconduct*)) same electrode*) and electrolyte*) not (wastewater or waste-water or degradation))	Search term searches for DSSC papers according to (1) the inclusion of components of DSSCs; using (2) (wastewater or waste-water or degradation) to exclude noisy data
Total	4104	#1 or #2 or #3 or #4	Combined search terms

Appendix 2. Different generations of solar cells

	Material	Main research target	Functional objectives	Examples	Commercialisation
First generation	Single-crystalline silicon	To make use of solar energy	To convert solar energy into current	Conventional solar cells	Now, 85–90% solar cell market
	Multi-crystalline silicon				
Second generation	Amorphous silicon	To decrease cost	To take silicon as the thin film	Silicon thin-film solar cell	Now, 90–100% thin-film solar cell market
	Microcrystalline (mc-Si:H) silicon		To use other semiconductors to replace silicon		
	Cadmium sulphide (CdS)		No vacuum processing	Compound semiconductor thin-film solar cells	In research, some of them will come to market soon
	Copper indium diselenide (CIS)		Low temperature fabrication		
	Cadmium telluride (CdTe)	To improve efficiency (*by nanotechnology*)	Enlarged the effective optical path for absorption		
	. . .		Photon management to shorten the path electrons and holes needed to travel		
Third generation	Cadmium sulphide (CdS)	To improve efficiency (*mainly by Quantum Dots nanotechnology*)	Utilisation of materials or cell structures incorporating several band gaps	Intermediate band gap solar cells	In research, very promising in the future
	Copper indium diselenide (CIS)		Modification of the photonic energy distribution prior to absorption in a solar cell	Up/down conversions	
	Cadmium telluride (CdTe)		Reducing losses due to thermalisation	Hot carrier solar cells	
	. . .			Impact ionisation solar cells	
	TiO2, ZnO. . .	Totally new principle (*by nanotechnology*)	Enlarged the effective optical path for absorption	DSSCs	Is coming to market
	Organic materials		Shorten the path that electrons and holes need to travel		
	. . .				