Challenges in moving from Incremental to Radical Low-Cost Innovation in Emerging and Transition countries

Institutional perspectives based on Rechargeable Battery Innovation in China and Point-of-Use Water purification Innovation in India.

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Abstract

Low-cost innovation is increasingly becoming the focus of attention of both firms and policy makers in Emerging and Transition Countries. Previous research has elaborated on the 'market based' view of low-cost innovations captured under various terminologies such as 'Frugal', 'Good-enough', 'Resource-constrained' etc. This study however demonstrates that low-cost innovation capabilities are profoundly influenced by the structuring of institutions, particularly the public-science system. The analysis in this paper is structured around innovation in rechargeable batteries in China and point-of-use water purification in India, drawing upon strategies at the Chinese firm BYD and Indian firm Tata respectively. Both the cases illustrate that diffusion oriented policies and weak university-industry links played a critical role in firms low-cost 'incremental' innovations. However as regards 'pre-competitive' research conducted in the public-science system, with the potential for better performing 'radical' technologies at lower costs, the current structure of institutions and firms strategies does not encourage firms to appropriate value from them into innovative output. This has important implications for both firms and policy makers in scaling-up low-cost radical innovations.

Keywords: Low-cost Innovation, Emerging markets, Innovation system, Innovation capabilities

Introduction

Management researchers have devoted considerable attention to the drivers of new product innovation and its impact on firm performance (Chesbrough, 1999; Teece, 1986; Tylecote & Ramirez, 2006). However research on innovation capabilities and strategies is largely based on the institutional structures of the developed west. Considerably less attention has been devoted to the study of innovation in Emerging and Transition Countries (ETC's) (Ayyagari, Demirguc-Kunt, & Maksimovic, 2011; Crescenzi, Rodriguez-Pose, & Storper, 2012). This is despite the fact that competitiveness of firms and regions in a globalizing economy rests on their ability to continuously develop, accumulate and exploit transnational capabilities (Cooke & Morgan, 1998; Ghoshal & Bartlett, 1988).

The majority of Customers in ETC's are very price sensitive and have very different requirements to developed countries in terms of product and service requirements. Developing low-cost and good-enough innovation requires different strategies to premium products for western markets. Williamson (2010) introduced the idea of 'Cost innovation' as solutions that offer similar functionalities to Western products at lower cost. An example of cost innovation is rechargeable Lithium-ion batteries (LIBs) made by the Chinese firm BYD which reduced production costs by 70% using a semi-automated process (Quan & Sanderson, 2013). Another popular concept is 'Frugal Innovation' (Bound & Thornton, 2012; Radjou, Prabhu, & Ahuja, 2012), which is not a re-engineered solution like BYD's semi-automated process, but a product or service that may be quite disruptive because firms offering them are not competing merely against a traditional rival but also against "non-consumption" since the potential customer might not have the financial means or access to the necessary infrastructure for using it. Indian firm Tata's 'Swach' water purifier that can remove 99% of disease causing bacteria is often cited as an example of frugal innovation (Tiwari & Herstatt, 2012). It was offered at a price point keeping in mind the affordability constraints of the 'base-of-pyramid' income group.

Despite the increasing attention on low-cost innovation in ETC's (Brown & Hegel, 2005; Govindarajan & Ramamurti, 2011; Prahalad, 2006; Prahalad & Mashelkar, 2010; Radjou et al., 2012; Zeng & Williamson, 2007), the existing literature is weak on the institutional antecedents of low-cost innovation. Firstly, most studies focus on the demand side in relation to customer affordability and accessibility. I argue that such a market-led approach on low-cost innovation puts a strong emphasis upon the need for 'quick' adjustments in reaction to an uncertain environment, rather than improving the efficiency of institutions, especially public-science, labour and finance.

Secondly, existing research on low-cost innovation in ETC's ignores the role of endogenous 'radical' innovation opportunities in remote areas from public-science institutions and the extent to which they are available to firms. Most of the advanced scientific and technological knowledge still exists in the triad countries (United States, Western Europe and Japan) and technology development in ETC's continues to rely on transfer of knowledge and expertise from the industrially advanced economies, moreover it is often inappropriate to the needs of low-income consumers (Kaplinsky et al., 2009). Archibugi and Pietrobelli (2003) also argue that the transfer of foreign technology per se has a negligible impact on learning unless accompanied by local innovation policies to promote learning, skills and technological capabilities. Therefore this study analyses the relevance of endogenous technology innovation, particularly 'radical' innovation, because industrial policies that are only aimed at catching up with the developed west are unlikely to meet the needs of most people in ETC's or enhance the financial performance of firms. The two gaps in prior research therefore lead to two research questions:

a.) How does the structuring of institutions lead to low-cost innovation capabilities among firms in ETC's?

b.) Can the existing set-up of public-science policies and mechanisms in ETC's ensure low-cost radical innovation?

The rest of the paper is organised as follows. The next section offers empirical and theoretical background of the study. Then I present the methodology. In the penultimate section, I provide a detailed analysis using two select cases. I finally conclude the paper with some key research observations and implications.

Background

The potential market size of ETC's has attracted management scholars and thinkers to investigate and analyse their role in globalization of technology and innovation. Ever since Vernon (1966) first proposed the product life-cycle theory, industrially advanced countries have been the focus of innovation diffusion studies. According to this classic notion, new products and technologies are first developed and launched in developed countries, and only later introduced in less developed countries when they have become increasingly mature, out-of-date, and obsolete in the developed market.

The large market potential of ETC's has led to an increasing competition among firms fighting for a share of the pie (Gadiesh, Leung, & Vestring, 2007; Iyer, LaPlaca, & Sharma, 2006). However, despite a growing middle class in ETC's, especially in Asia, most consumers still cannot afford western consumption and are often constrained by other bottlenecks, such as poor public and private infrastructure or limited service availability. As a result, firms have started to develop market-specific local innovations that are characterized by high-value at low-cost, and potentially disruptive. The rising demand for low-cost products among the aspiring consumers of the developing world will drive an enormous global market for low-cost, high-quality products.

In the last decade, low-cost innovations in ETC's have been explored extensively from many different perspectives (Agarwal, Grottke, Mishra & Brem, 2017). Although the increase in both academic research and business interest in this field has established the importance of emerging markets (Zeschky, Widenmayer, & Gassmann, 2011; Zedtwitz, Corsi, Soberg, & Frega, 2015) and developmental issues (Leliveld & Knorringa, 2018), however it has also led to numerous and often confusing terminologies, for e.g. 'Frugal', 'Good-enough' and 'Resource constrained', without clearly defining their scope and boundary. Most studies are conceptual in nature and apply terminologies to various cases in a cursory manner (see Hossain, 2017), rather than deep qualitative insights.

Zeschky, Winterhalter, and Gassmann (2014) attempt to clarify the boundaries of various terminologies. They conceptualise the structural differences between the various innovations based on two dimensions of technical and market novelty. Cost innovation is low in both dimensions, good-enough innovation is at the intersection of low and medium on both dimensions, whereas frugal innovation is high in market novelty and medium in technical novelty. This suggests that the different natures of cost, good-enough and frugal innovation will require a different set of capabilities with frugal being the most challenging. However, the boundaries are still a bit blurry since it may be hard to define when the technology or market novelty level is low, medium or high (Quan, Loon, & Sanderson, 2018).

The literature however appears to be lacking in theoretical underpinnings, specifically they seem to evade the fact that particular forms of innovation may be a result of specific structuring of institutions and not just a result of firms overcoming resource constraints and institutional voids. In addition, the relevance of advanced scientific skills in achieving low-cost innovation has only been dealt with superficially by illustrating in hindsight how advanced science and technology can lower costs (Rao, 2017), rather than offering a prognosis of what institutional mechanisms need to be in place to ensure development and commercialisation of low-cost innovations. A more exhaustive review of the various terminologies and examples of low-cost innovations is not imperative because this has been sufficiently dealt with (see Agnihotri, 2015; Hossain, 2017), instead I focus on the role of institutions in developing low-cost innovation competencies and offer a critique of relevant 'conceptual' studies that support my justification for this study.

The presence of Lead Markets

The emergence of ETC's as a hub for low-cost innovations suggests their role as "lead market" (Herstatt & Tiwari, 2017; Tiwari & Herstatt, 2012). A "lead market" is a country or region where an innovative design is first widely accepted and adopted. Tiwari and Herstatt (2012) argue that despite the generally low customer sophistication in ETC's, innovator sophistication enables designing cost-effective, "good enough" solutions that can meet the needs and aspirations of consumers in a highly competitive market. Similarly, Petrick and Juntiwasarakij (2011) assert that the key to innovating in and for emerging markets is to understand the importance of scale, and to address local consumption patterns where utility is more valued than efficiency. They also stress that emerging countries are not just about the economics of low-cost labour arbitrage, but also possess a growing talent pool that is in tune with the realities of their locale. This implies that firms need access to a competent and sufficiently large technical base with in-depth knowledge of the targeted consumers. However, access to technical skills is fundamentally dependent on structuring of institutions. Furthermore developing low-cost solutions is not only dependent on consumer demand and competition for a share of the pie, it also requires firms to have an innovation model that supports them in identifying specific solvable problems and proposing possible modes of participation within the current institutional set-up.

The role of Institutions

The idea of a National Innovation System (NIS) is often used to understand how national institutions contribute to generation and diffusion of new technologies, and how government and firms negotiate policies to influence the innovation process (Metcalfe, 1995). The key components of innovation systems include firms of different types, public and private research organisations, education and vocational training institutions, financial institutions, business associations, research consortia etc. (Whitley, 2002; Whitley, 2007, p. 75).

Although technological 'catch-up' and economic development have always been central to the NIS concept (Lundwall, 2007), the idea was conceived on institutional characteristics in developed countries (e.g. Japan, USA, Germany, Sweden) with ETC's largely absent from discussions in early literature. Gu (1999) suggests that technology catch-up with the west, based on industrial models of the west and capital from the west is the best way to augment the innovation system in ETC's. Though "imitation" catch-up activities may be considered as innovations since their adoption involves adaptations to the local context (Dutz, 2016) and may also positively correlate with new-technology development (Zhang & Zhou, 2016), ultimately ETC's must implement an Innovation policy that is most appropriate for their country's unique socio-economic structure.

While 'best practices' implemented in developed and recently industrialised countries such as Korea can offer useful guidance, a 'one size fits all' solution is unlikely to align with the local context (Crescenzi, Rodríguez-Pose, & Storper, 2012; Niosi, 2010). However National innovation systems may be weakening as different countries and also different regions within the same country may have advantages in different sectors, thus requiring different logics. Also key features and characteristics of institutional frameworks governing finance, labour and public-science systems encourage firms to develop innovative competencies in different ways, and so generate different types of technology innovation in different societies (Whitley, 2007, p. 191).

Innovation in ETC's - overcoming Institutional Voids or Institutions as enablers?

Bhatti and Ventresca (2013) argue that, in addition to resource constraints faced by ETC firms upstream of their value chain in order to innovate and affordability constraints downstream in meeting the needs of the base-of-pyramid, firms are challenged by complex institutional voids characterised by the lack of institutional facilities, norms, and regulations needed for a well-functioning economy. This is because of constraints on the limited capacity of governments in ETC's to pursue various issues at a time. Ernst, Kahle, Dubiel, Prabhu, and Subramaniam (2015) claim to draw on institutional theory to explain three antecedents of affordable value innovation - bricolage (creative combination of scarce existing resources to develop new solutions), local-embeddedness of a firm and product standardization.

Both the above studies seek to explain how firms overcome institutional constraints rather than understanding how key features and structure of institutions in itself may encourage firms to develop low-cost innovations by building distinctive 'organisational' capabilities in accumulating and deploying their resources. While institutional voids generally limit business activity by increasing transaction costs and therefore represent a hurdle for firms and entrepreneurs (Soni & Krishnan, 2014), they may encourage development of new innovative competencies. Institutions can indeed facilitate innovation if firms have an adaptive ability that allows them to react to and play a more active role in overcoming any institutional constraints by taking over certain functions of institutions (Greeven, 2013).

Moreover the development of specific ways of innovating depends not only on the strength of institutions, but also on the complementarity of key institutions. Complementarity entails that the comparative advantage of a region or country depends upon the extent to which institutions are compatible with one another (Bruno, 2000). For example, a robust venture capital (VC) market is dependent upon the existence of clear rules governing intellectual property rights (Fenn, Liang, & Prowse, 1995). Because of institutional complementarity, different kinds of learning, cooperation and competition take place under different institutional settings (Whitley, 2007, p. 84). Therefore both the strength of institutions and extent of complementarity lead to certain firm strategies and organisational forms to become prevalent.

Developing Capabilities for Low-Cost Radical Innovation

Strategic cost-innovation in high-tech firms that is primarily a result of efficient management of low-cost labour may not be perceived as genuine technological innovation (Zheng & Wang, 2012). Moreover any Innovation is likely to be process innovation, new techniques that lower production costs. Also innovation for the base-of-pyramid, though market disruptive, could be a result of incremental improvements to existing technology and not a result of radical technology development (Agnihotri, 2015). However radical technological innovation is an important driver of the growth, success, and wealth of firms and nations (Tellis, Prabhu, & Chandy, 2009). Further, radical innovation offers novel functionalities and distinct customer benefits, which are difficult to imitate, and provides distinctive competitive advantages for the longer term (Bao, Chen, & Zhou, 2012). Li, Li, Wang, and Ma (2017) suggest that because high resource consumption and high uncertainty are two of the most critical challenges for radical technological breakthroughs, for firms in ETC’s that are characterized by significant resource deficiency and high contextual uncertainty, it becomes necessary that they adopt resource acquisition and resource accumulation for effectively managing their resource portfolios, and also embrace resource flexibility and coordination flexibility for effectively managing their contextual uncertainties.

A useful way of dealing with ‘adaptive’ and ‘flexible’ organisational capabilities is the ‘dynamic capabilities’ view of firm (Teece, Pisano, & Shuen, 1997). Dynamic capabilities can be defined as the firm’s processes that integrate, reconfigure, gain and release resources to adapt to and even create market change (Eisenhardt & Martin, 2000). Thus, by systematically coordinating and directing particular resources through firm-specific routines, ‘dynamic capabilities’ enable creation of new products and processes by responding to changing market circumstances. The changes can range from incremental changes in products and processes to more radical transformation of competences and knowledge.

Innovation process involves a search for new information outside the existing knowledge base, and is a crucial dynamic capability, especially within high-technology firms. A common feature across successful Innovation processes is explicit linkage between the focal firm and knowledge sources outside the firm, including with researchers at universities, government laboratories and other research oriented firms. Therefore an organisational capabilities view of a firm considered in isolation from the institutional environment, particularly the nature of the public-science system and engagement of firms with them, cannot fully explain how firms organise new resources and develop their innovation capabilities (particularly technological).

Uncertainties and costs of conducting research could be minimized if institutions facilitate firms to access radical technologies and skills in the public-science system. By systematically coordinating and directing specific inputs for radical innovation, such as human, technology and materials through firm-specific rules and procedures, firms in ETC’s may then develop distinctive capabilities for low-cost innovation that provide unique competitive advantages.

Summing up, though research on low-cost innovation has thus far been enriched by several empirical case studies, and although some studies have attempted to integrate institutional theory to explain low-cost innovation, I believe that none explain how firms come to develop such ‘capabilities’ and what role radical innovation plays. Previous research has elaborated on the ‘market based’ view of low-cost innovations captured under various terminologies such as ‘Frugal’, ‘Good-enough’, ‘Resource-constrained’ etc. This study however argues that low-cost innovation capabilities are profoundly influenced by the structuring of institutions.

Methodology

Case Study Method and Case selection

This research uses a case study approach (Yin, 2013), and qualitative evidence is not used to build a generalised theory but rather to provide examples and opinions that reflect various features and characteristics of institutions and markets. Because the study offers a prognosis of low-cost and radical innovation capabilities in ETC’s, exploratory case studies are useful. The study looks at innovations within two technological domains: Rechargeable Batteries and Point-of-use (PoU) water purification. The study draws on two successful low-cost innovations launched in an ETC context – BYD’s low-cost manufacturing of rechargeable LIBs that started in China in 1995 and Tata’s ‘Swach’ low-cost water purifier launched in India in 2009, both often described in the literature as examples of low-cost Innovation.

The two domains were chosen because it allowed placing the two innovations in the context of new and potentially radical technology developments in respective countries, supporting analysis of the impact of institutional dynamics on the nature of innovation capabilities. In the case of China, for e.g. I touch on China’s Collaborative Innovation Centre in Chemical Science and Engineering (CICCSE) based at Tianjin and Nankai Universities (McGilvray, 2016) who have developed a potentially radical low-cost battery technology - Sodium-Carbon dioxide batteries (Kramer, 2016). I particularly touch on this invention at CICCSE because the current challenge in a new battery technology is not just the speed of charging, but more importantly charge density. The Sodium-Carbon dioxide batteries can store much higher charge (currently five times) compared to LIBs. In the case of India, I touch on advanced nano-materials for water purification developed at Indian Institute of Technology Madras (IITM) (Gravotta, 2013). I have particularly picked this technology because the challenge in developing a low-cost purifier is not just about being ‘good-enough’ in killing the bacteria and removing turbidity, but meeting more complex water purification challenges at low-cost. The IITM technology can remove Arsenic and other toxic metals.

Data Sources and Analysis

The research is based on (a.) sizeable secondary archival data from mass media and academic case studies, (b.) detailed analysis of patents and (c.) additional primary data (see table 1). Interviews in mass media are accepted as credible as it is presumed that they cannot be released without the consent of interviewees (Lim, Han, & Ito, 2013). Further, technical information in mass media sources were also cross checked for accuracy by comparing with peer reviewed scientific publications. In the case of India, I was also able to gain expert insights through primary interviews with academics active in low cost water innovation – Prof. Murali Shastri who was previously Chief Scientific Officer at Tata and Prof. T Pradeep, principal investigator of the IITM Nanotechnology Innovation.

Table 1: Key Sources of Data

Subject	**Data type and description**	**Sources**	**Period**
Rechargeable Battery Innovation in China	Secondary data on Battery Innovation and Vertical diversification at BYD. Three mass media sources and five case studies.	Mass Media: Dongmei, Binbin, Yanyan, and Duan (2010); Gunther (2009); IHS Markit (2010) Case studies: Huckman and MacCormack (2006); Quan, Loon, and Sanderson (2018); Wan, Donsheng and Chatopadhyay (2013); Wang and Kimble (2010); Wang and Yang (2013)	2006-2018
	Patent analysis of BYD's battery innovations	LENS database	2000 – May 2018
	Secondary data on Sodium Carbon-dioxide (NaCO2) battery.	Mass media: McGilvray (2016)*;* Kramer (2016); Scientific Publications:	2016-2017

	Two mass media sources and two Scientific publications.	Hu, et al. (2016); Hu, et al. (2017)	
Point-of-Use Water Purification Innovation in India	Secondary data on Tata Swach. Seven mass media sources, Tata's Quarterly Magazine 'Tata Review' and a Patent application.	Mass media: AFP (2009); Chandra, 2010; Iyer (2009); Murray(2011); Sharma and Nupur (2012); Singh (2011); Subbu (2009) Tata Review: Rodrigues (2010) Patent application: Sastry, Rautaray, Parida and Kandukuri, 2010	2009-2012
	Patent Analysis of Tata's Water Purification Innovation	LENS database	2010 – May 2018
	Secondary data on IITM Nanomaterials Innovation. Seven mass media sources and two scientific	Mass media: Gravotta (2013); Janin (2016); Jayaraman (2007); Kodati (2016); Murali (2007); Prasad (2016); Singh	2007-2016

	publications.	(2008); Scientific Publications: Kumar, et al. (2016); Pradeep and Anshup (2009)	
	Primary data: Interview with Previous Chief Scientific Officer at Tata.	Prof. Murali Sastry, IITB-Monash Research Academy	2017
	Primary data: Interview with Principal Investigator of IITM Nanomaterials Innovation.	Prof. T. Pradeep, IITM	2017

Patent data was analysed using LENS[2] database to infer Innovation priorities and strategies of firms. I have used the Cooperative Patent Classification (CPC) which includes the same sections as the International Patent Classification (IPC), plus a Y section for tagging emerging technologies or technologies spanning several sections of the CPC. Patent data are a relevant measure for knowledge development and diffusion, and have been widely used as a measure of inventive activity and knowledge flows (Meyer, 2002; Stephan, Schmidt, Bening, & Hoffman, 2017). Patent counts can thus provide a proxy for a firm's innovation capability and future technological trajectory. However, for novel technologies that are not yet commercial,

[2] http://www.lens.org/

generally little or no data is available, as firms usually seek to keep their research activities secret from competitors. Nonetheless, patent data may still help understand and analyse the Innovation direction of a firm.

Water purification related patents can be found under CPC C02F (Treatment of water, waste water, sewage and sludge). Battery related technologies can be primarily found under CPC's H01M (Process or means for conversion of chemical to electrical energy), Y02E60/12 (new technological developments in battery). Table 2 below shows the exact CPC numbers used for searching patents on rechargeable batteries and auxiliary non-active parts and safety devices. I also used a keyword search strategy for the auxiliary parts and system design search.

Table 2: Battery related Patent Analysis search strategy

Description	**Search strategy**
LIB technologies	CPC: H01M 10/052*, Y02E 60/122, Y02T 10/7011
Alkaline batteries (not within H01M6 i.e. Primary or non-rechargeable batteries), Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd)	CPC: H01M 10/28*, 10/24–10/32, 4/24*, 4/24–4/34, 10/345, Y02E 60/124
Regenerative Fuel Cells (these can be classed as Secondary or rechargeable Batteries)	CPC: H01M 8/188, Y02E 60/528
Auxiliary parts or system assembly	Strategy 1 – CPC search for Patents related to non-active parts and safety devices under H01M but excluding primary

	and fuel cells: H01M2/*, H01M2200* NOT (H01M6* OR H01M8* OR H01M16* OR H01M2250*) Strategy 2 - Keyword search e.g. heating circuit, end cover, supply system, power system, control system, cooling plate, battery separator, electric connector etc.

Findings and Discussions

Rechargeable Battery Innovation in China

Early Diffusion-Oriented Industrial Policy and Cost-Innovation

BYD Co. of China has emerged as one of the major rechargeable battery manufacturers today. It was founded in 1995 by Wang Chuanfu, a chemist and government scientist to manufacture rechargeable batteries, when the battery market in China was huge, but dominated by Japanese imports at very high prices. By 2009, the company occupied 10% of global market share for LIBs and was the second largest LIB supplier for mobile phones in the world (Shirouzu, 2009). Today it occupies 25% of the market share (Lux Research, 2017)

BYD's entry and gaining a share from Japanese rivals in a high growth market for LIBs is attributed to developing new low-cost 'process' innovation capabilities as a result of replacing expensive machinery with a semi-automated line (Quan & Sanderson, 2013). Moreover, BYD also reduced processing cost by using materials in products that were less sensitive to humidity and required less dry room space (Huckman & MacCormack, 2006). Zeschky et al. (2014) categorise BYD's battery innovation as cost innovation which is low in technical novelty and market novelty, because it offers same functionality as other LIBs, but at a lower cost. However Rao (2013) suggests that BYD is a low-cost product made using sophisticated technology. Rao does not suggest in what way BYD's technology is sophisticated, however arguably, using alternative materials in their products that were less sensitive to humidity and avoided larger expensive dry rooms for processing demonstrates technological sophistication. Quan et al. (2018) argue that BYD's low-cost innovation is in response to price-sensitive customers. In 1998, BYD could sell a mobile phone battery for $3 compared to $8 for Japanese batteries, whilst still maintaining a profit margin of 60%.

Nevertheless, presumably such low-cost capabilities were made possible due to the composition of China's labour institutions, i.e. availability of a huge pool of low-cost yet high-quality labour for R&D in addition to low-cost unskilled labour for manufacturing operations. Further, BYD efficiently manages and retains its highly skilled human resources by recruiting graduates from the best Chinese universities and offering them plenty of career progression opportunities and incentives (Gunther, 2009; Quan, et al., 2018). It was especially easy to find good talent in the early days because of the lack of job opportunities for graduates.

Thus it appears that BYD's innovation capabilities emerge from a strategic approach to managing and training its human capital. In the early 1980's, China was introducing major institutional and policy changes affecting its technological learning system. During this time it was heavily dependent on foreign education and technology transfer (Xie & White, 2006). Chinese universities focused on producing engineers and scientists than on training them to do advanced research, hence the government had to sponsor Chinese students to pursue higher education abroad, especially USA. The 1990s saw major policies in advanced manufacturing and quality systems, however Chinese firms relied on Multi-National Corporations (MNC's) for technological know-how. Therefore China's 'diffusion' oriented policies in the 1980s and 1990s did not encourage close long-term links between domestic firms and local university researchers and the engagement was usually limited to solving short-term problems.

However the weak science-industry link was balanced by a large pool of highly skilled graduates (strong labour institutions) in enhancing firms capabilities, especially in particular sectors such as in Electronics. Further, BYD worked closely with customers, rather than the public-science system, to develop innovation competencies in low-cost-high-quality batteries. For example during BYD's early years, Motorola sent its engineers to work on-site and closely with BYD engineers to improve the quality of its batteries. Six months later, BYD earned the six-sigma certification, an international badge of quality Motorola itself invented (Fishman, 2005, p. 215). By relying on existing technological knowledge around LIBs, and collaborating with customers in building firm specific know-how in low-cost process innovation and in developing new organisational routines in quality, BYD was able to outdo its Japanese rivals. Thus it can be argued that the local labour composition and weak university-industry interaction encouraged the integration of existing know-how with support from key customers, leading to re-engineering the production process from a largely automated to a semi-automated method.

Firms Innovation Dilemma – why focus on existing technology?

BYD developed its own internal R&D and manufacturing capabilities with little links into the public-science system through the formation of a Central Research Department in 1997, renamed as the Central Research Institute (CRI) in 2005. In general, the cooperation between universities and enterprises remains weak in China and firms do not have mechanisms to effectively absorb universities' research output (Boeing, Mueller, & Sandner, 2016). Zheng (2014) argues that the key factors for Chinese firms to be technologically innovative are more internally driven, in alignment with the resource-based and competency-based strategic perspective. High-technology Chinese firms focus heavily on developing internal assets such as technology champions, entrepreneurship, organisational structural reform, learning and knowledge creation, as well as building a strong financial base (i.e., utilising stock market listings to generate capital for growth and expansion). The CRI at BYD employs more than 300 researchers involved in cross-cutting R&D in areas such as energy storage, automobiles and IT. A statement on the website about CRI reads:

> "*It not only commits to a variety of new materials research and development, but also reserves the high-level compound talents and provides continuously strong power to the development of BYD*."

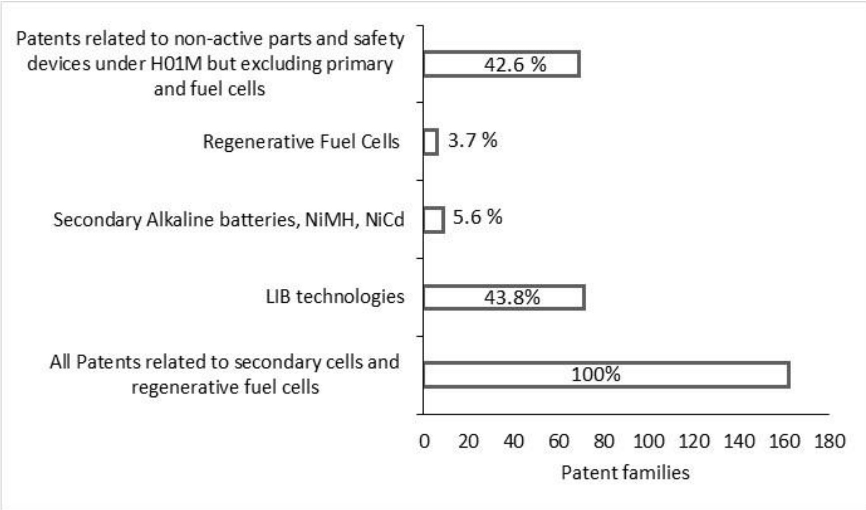
Moreover, the vision statement reads:

> *"By 2015, to own several core technologies in acoustics, photonics, electronics, calorifics and magnetics areas; to be capable of developing novel products based on metals, ceramics, polymers and their complex. By 2020, to be one of the top R&D centers nationwide. By 2030, to be one of the top R&D centers worldwide."*

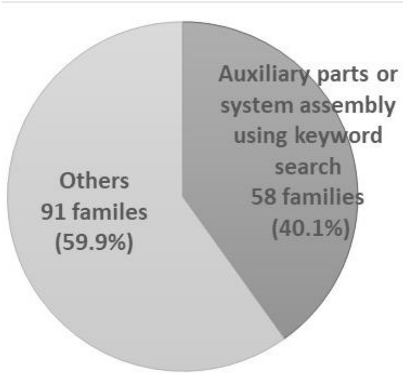
Interestingly, though BYD has vertically diversified its manufacturing beyond batteries into other industry sectors such as transport and solar, however its growth in these sectors is still a result of its innovation and production capabilities around its core technological knowledge in LIBs (Wang & Yang, 2013). For. Example, the DENZA electric car manufactured by a 50:50 joint venture between BYD and Daimler Mercedes (BYD Daimler New Technology Co., Ltd. or BDNT in short), combines Daimler's engineering expertise as a worldwide leader in safety technology and quality excellence with BYD's low-cost LIB technology (IHS Markit, 2010).

Thus from venturing into new end application sectors such as automobiles and externally sourcing technological knowledge in these sectors, BYD's strategy appears to be to reinforce and augment its distinctive capabilities in low-cost innovation around its original core technological domain i.e. LIBs. Such a diversification strategy may not however help build-up capability for 'radical' innovation in new Battery materials. I also analysed BYD's battery storage related patents over the last 2 decades between the year 2000 and May 2018. From granted Patent data (families), I found LIB technology to be 43.8% (71 families) of all rechargeable secondary battery and regenerative fuel cell related patent families (162) (see figure 1a). Further 42.6% (69 families) for secondary batteries relate to non-active parts (H01M2) and safety devices (H01M2200). A keyword search for the most common auxiliary parts or system assembly details in the title revealed 61 families for secondary cells (figure 1 b) which is close to the CPC search for non-active parts and safety devices. I also noted that under Y02E60/12 (22 families), LIB patents are 59 % (13), NiCd and NiMH are 22.7% (5) and auxiliary parts or assembly details are 18.2% (4) (see figure 1c). As regards application of battery technology, 12.8% (23) of all families under H01M and Y02E60, are also tagged under Y02T which relate to new technological developments in green transportation (see figure 1d).

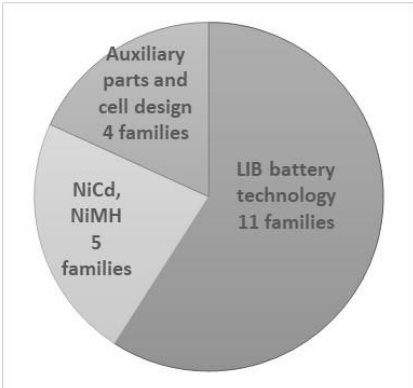
Patent data therefore suggests that most focus is clearly on existing LIB technology, auxiliary parts, assembly details and application to transport. This may also indicate that BYD's approach is largely generalist, emphasizing the use of LIB technology into useful products and applications, by integrating multiple auxiliary technologies into a product. Newer influential inventions in secondary battery technologies will require researchers with greater depth of expertise in materials other than LIB technology. In short, I see BYD making an effective effort to fill gaps in its innovation capacity through focusing on applications and vertical diversification.



a. Composition of Patents related to secondary and regenerative fuel cells



b. Auxiliary parts or system assembly search under secondary cells using keyword search (excluding regenerative)



c. Composition of Patents under Y02E60/12 (new battery technology)

d. Overlap between battery technologies and green transportation

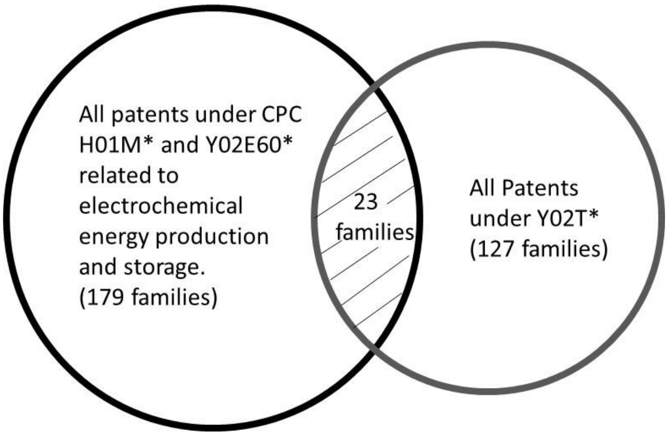


Figure 1: Analysis of BYD's patents between year 2000 and May 2018.

Zhou and Wu (2010) argue that a firm with a broad knowledge base is more capable of developing radical innovations through internal knowledge sharing rather than acquiring external market knowledge acquisition, whereas a firm with a deep knowledge base is more capable of achieving radical innovation through enhanced market knowledge acquisition rather than internal knowledge sharing. BYD falls in the later with deep knowledge in LIB technology, and it can be argued that its vertical diversification is a result of aligning external market knowledge with internal knowledge. Though vertical diversification may have a strong impact on innovation, because it fuels cross-fertilization between different technology fields, BYD's strategy in applications such as Automotive appears to be 'creative imitation' through 'reverse engineering' external Innovations, primarily by using publicly available non-patented literature (Dongmei, Binbin, Yanyan, & Duan, 2010; Wan, Dongsheng, & Chattopadhyay, 2013; Wang & Kimble, 2010) . Bao, et al. (2012) suggest that external knowledge generated by other organisations is a viable strategy that firms can leverage to build radical innovation, however this is conditional on learning achieved by committing to strategic alliances and embedding in external networks. The public-science system is an important source of radical innovations, however firms wishing to access them have to make considerable investments to enhance their 'absorptive capacity', by hiring experienced researchers to conduct more generic research (Cohen & Levinthal, 1990) .

Public Science policy, priority Economic sectors and Firms Innovation Capabilities

Because of the weakening of incremental innovation strategy followed by many Chinese firms aimed at reducing costs, primarily due to competition from countries in ASEAN[3], the Chinese government has focussed on endogenous innovation in the last 10 years (Gu, Serger, & Lundvall, 2016) including the establishment of collaborative innovation centres (CICs) to

[3] Association of Southeast Asian Nations

improve Collaboration between Universities, Industry and government. There have been about 38 CICs across the country since 2012 (McGilvray, 2016), categorised into four types: scientific frontier-oriented, industry-oriented, regional development-oriented and cultural heritage innovation-oriented (Fan, Zou, & Lv, 2013). Scientific frontier-oriented CICs cultivate world-class scientific research and talent in the natural sciences whereas the Industry-oriented CICs focus on fostering emerging strategic industries through advancements in engineering and manufacturing. The regional development oriented are funded by local governments and may be science or engineering related, however the focus is local needs rather than 'generic' technologies. CICSSE is a scientific frontier-oriented centre which receives around $7.5 million a year in research funding and flexibility to choose its research direction.

An important potentially radical nanotechnology innovation at CICSSE is the Sodium–Carbon dioxide battery (McGilvray, 2016). In principle, these batteries are more energy efficient than LIBs (Hu, et al., 2016; Hu, et al., 2017), as well as 'cheaper' because of the abundance of Sodium and Carbon dioxide (Kramer, 2016). Because 'diffusion oriented' Science policy that is closely linked to current problems is unlikely to encourage strong connections between industry and researchers in public-science institutions around 'pre-competitive' fundamental research on remote topics that seeks to explain general phenomena, one would hope that high-technology research centres like CICCSE would enhance the National capacity for more radical innovation.

However industrial interaction between CICCSE and industry (LIB developer Tianjin Lishen and electronics manufacturer Samsung) has focused on improving current technology around LIBs (McGilvray, 2016), presumably because the new Sodium-Carbon dioxide technology is not yet commercial, and translating it into practical benefit is not trivial. It can initially cost circa $500 million to set up a small manufacturing line and conduct further research to make a new battery product (Martin, 2016). Moreover, in contest with the Chinese government's own focus on endogenous innovation, the government also sees LIBs as a hugely significant industry in the 2020s and beyond (Ryan, 2017).

By 2020, the Chinese government wants to double production of electric cars with LIB technology, and has heavily subsidized the electric car industry, turning BYD into the largest producer of low-cost electric vehicles globally. However given the uncertainties in the electric car market and government subsidies, BYD further diversified into monorail mass transit and spent nearly $725 million researching and building a prototype system that involved its batteries (Burkitt, 2017). In Sep 2017, BYD installed its first commercial system (Clover, 2017), purportedly at one fifth the cost of comparable systems, and BYD hopes to bag contracts from many cities across the world. Given that the Chinese government has supported the creation of a 'too big to fail' LIB industry, diversification though expensive initially, is a strategic option for BYD against market uncertainties.

'Pre-competitive' research can result in radical technologies, however when research in universities and other public research organisations is facilitated and coordinated by government around its public objectives and mission, and not a consequence of strategic R&D investments by autonomous firms, technology development will tend to be restricted to a few priority areas of economic interest for the government rather than being 'generic' (Whitley, 2007, p. 70). Therefore though China's high-tech research, whose costs are primarily borne by the government as in the case of CIC's, may lead to newer technologies, however when government policy is focused on current priority economic sectors (Liu, Schwaag Serger, Tagscherer, & Chang, 2017) and industrial engagement is largely around solving current problems within those sectors, the primary emphasis in Chinese firms Innovation strategy will be tweaking existing technologies or diversifying into sectors that blends their core capabilities with other current external technologies, and not much research effort around developing "new to the world" scientific ideas and technologies (Gupta & Wang, 2016; Williamson & Yin, 2014).

The Sodium-Carbon dioxide batteries can currently store five times more charge and theoretically achieve ten times for the same weight as LIB, and use cheaper and more abundant materials, i.e. Sodium and the freely available Carbon dioxide in the air. However, commercialisation may be challenging because it will be difficult for firms to acquire radically new skills to scale such technologies and help realize low production costs in addition to low materials costs, if they follow a rather passive approach to working with public-science institutes or restrict to incremental improvements to current technologies, and do not actively pursue new technological developments through strategic investments.

Further, in addition to recruiting recent graduates such as seen in the case of BYD, firms may have to focus on recruiting leading scientists and highly experienced researchers who have spent significant time in public-science institutions even after their PhDs in order to commercialise radical technologies that carry a significant level of technical and economic uncertainty, especially in the early stages. Therefore the government's inputs into supporting breakthrough research at its elite research institutions will not automatically lead to the creation of new products and a financial value for both firms and governments. Chen, Vanhaverbeke, and Du (2016) also note that when market information dictates new business opportunities, Innovative Chinese firms contract and outsource technological problems that are not 'translational' to universities. Overall, given the economic priorities of the government and the passive engagement with universities around current problems, it can be concluded that Innovative Chinese firms such as BYD may see no need to develop or internalize high levels of technological competencies. Such strategies will therefore limit Chinese firms from acquiring skills for radical technology development.

Point-of-use (PoU) Water Purifier Innovation in India

Unserved market and Frugal Innovation

In India, access to improved water supply and sanitation remains insufficient. Poor quality of drinking water leads to various diseases and high death rate. The ‘Point-of-use’ Water purifier market in India was dominated for a long time until late 2000 by Aquaguard from Eureka Forbes with a price between Rs 5,000 (~ US $75[4]) and Rs 10,000 (~ US $150), which was not affordable to most Indian families. Efforts were made by various companies to build affordable water purifiers, e.g. Hindustan Unilever’s PureIt water purifier. But PureIt ran on battery (electricity) and it cost around Rs 1,800 (~ US $ 27, battery included) (Ruan & Hang, 2013).

In response to the affordability constraints of low-income consumers, in Dec 2009 Tata launched the “Swach” filter system that uses silver nano-particles infused in rice husk ash (RHA), runs on zero electricity (Rodrigues, 2010), and was reportedly claimed as the world’s cheapest household water purification system (Rediff Business, 2009). RHA reduces the turbidity or cloudiness of the water entering the filter and removes most of the toxic organic impurities, and moreover according to Prof. Murali Sastry, the silver nanoparticles kill 99% of disease causing bacteria. Developed primarily by Tata groups Tata Chemicals with help from other Tata entities, namely Tata Research, Design and Development Centre (TRDDC) and Titan Industries, Tata Swach came in two variants, priced at Rs 749 (~ US $11) and Rs 999 (~ US $15), at a time when most other purifiers cost more than Rs 2,000 (Rediff Business, 2009).

Despite the existence of a favourable market and supporting factors such as strong country specificity of distribution networks, technologies such as Swach, although effective and

[4] 1 US $ ~ 67 Indian Rupees (Rs)

relatively easy to use, had its own adoption challenges. For instance, though the filters can be bought from grocery stores, purify 3,000 litres and last six months for a family of five, and cost less than a rupee (1.5 cents) per day per family (Rodrigues, 2010), timely accessibility of filters is a key determinant of success in rural India with poor transport and retail infrastructure. However, a key innovation, the Tata Swach 'Fuse', indicates the capacity remaining in the filter, giving householders time to buy a replacement, and automatically shuts it off once the purifying admixture is exhausted (Rodrigues, 2010). The fuse is thus an important factor in timely product accessibility.

Firms Innovation dilemma – why focus on basic low-risk technology?

Though better technology, and timely accessibility of accessories such as filters, are likely to be important determinants of PoU water treatment product adoption (Null et al., 2012), most evidence suggests that price considerations dominate the other elements (Ashraf, Berry, & Shapro, 2010; Kremer, Miguel, Mullainathan, Null, & Zwane, 2009). Therefore Tata Swach's success is mostly due to trade-offs between product design attributes and price acceptable for a potentially large lead-market (Murray, 2011). Though the basic product removed 99% bacteria and many organic impurities, it is unable to remove inorganic impurities, particularly Fluoride and metal ions such as Arsenic. No 'simple' conventional technology exists that addresses multiple water quality problems such as bacterial and heavy metal contamination together or Heavy metals, turbidity, pesticides and salinity together (Vijay Lakshmi, Nagrath, & Jha, 2011). However, Swach still allowed significant gains to consumer within their affordability limits compared to previous consumption of unfiltered water.

India has built a robust innovation climate around innovations that deliver high value at low costs for resource-constrained consumers at the bottom-of-pyramid (BoP), particularly in addressing pressing global problems in clean water, healthcare and energy (Bhati, 2013;

Bhattacharya, Shilpa, & Bhati, 2012). Consumers at the BoP not only look for affordable products, but also products that entail simplicity and do not comprise non-value adding unnecessary features, user-friendly in both composition and function, and products that are durable (Taube, 2018). Such scarcity induced innovations that are affordable yet disrupt a market and serve a significant volume of customers have also been called frugal innovations (Radjou, et al., 2012).

An important premise of frugality is that low cost does not mean low- tech (Bound & Thornton, 2012). 'Frugal innovation' is not just low-tech or cheaper versions of existing technologies, and can combine low and high technology, for e.g. in the case of Tata Swach, combining RHA (low-tech) with silver nanotechnology that is considered high-tech (Wooldridge, 2012). It appears that this is based on the assumption that nano-silver is something new given the increase in number of consumer applications since early 2000's. However, nano-silver has been used for nearly a century and was registered as a biocidal material in the United States in 1954 (Nowack, Krug, & Height, 2011). Tata Chemicals innovation was in finding the right chemistry to bind silver nanoparticles to RHA (Chandra, 2010), and it is arguable whether this is advanced cutting-edge technology. Whilst the design of the system may be considered novel, silver nanotechnology is in itself not new and neither does Tata Chemicals claim the 'right' chemistry to bind silver to RHA as unfamiliar. Tata Chemicals claims are in fact about the antimicrobial effectiveness of a specific composition of RHA and nano-silver (see Sastry, Rautaray, Parida, & Kandukuri, 2010), which I therefore argue is incremental innovation.

India's present status of Nanotechnology R&D is still not comparable to developed countries such as US, Japan and Germany, or even China's (Dong, et al., 2016; Ghosh & Krishnan, 2014). Though India has strengthened the supply side of the innovation in the public-science system, however there is less clarity in terms of priority areas unlike China which has clear strategies and priority applications (Anand & Sarma, 2013). Further, India's policies are still weak in supporting scalability of R&D, including a lack of Venture Capital funding particularly for Physical sciences based start-ups (Kodati, 2016). Advanced and more radical nanotechnology innovation requires institutional complementarities between a strong 'mission' oriented public-science system and the existence of a strong venture finance system to commercialise high risk nanotechnologies with a long gestation period. It appears that a weak interaction between public-science institutions and firms in India, compounded by the lack of skills to commercialise scientific output may have led to a focus on low-cost, low-risk incremental technologies in both public-science institutions and firms (Ali & Sinha, 2014). These factors may also be responsible for a lack of industry participation and VC confidence in more advanced high-risk nanotechnology R&D.

The initial ideas that led to the development of Swach were in fact initiated by Prof. PC Kapoor at a public-science institution, 'Indian Institute of Technology Kanpur (IITK)' in the 1980s. After his retirement he continued his work at Tata's research arm 'TRDDC' where a rudimentary device 'Sujal' was developed in late 1990s using RHA and pebbles. However, Sujal wasn't commercially successful because of its inability to remove many bacteria (Rodrigues, 2010). The project was revived in 2006, and it took two years for the development of Swach when Tata Chemicals at their Innovation centre found the right chemistry to bind silver nano-particles that has significant antibacterial properties to RHA. Interestingly the Chief Scientific Officer of Tata Chemicals Prof. Murali Sastry had also moved in from a public-science institution, the 'National Chemical Laboratory'. Overall the development journey of even a low-cost water purification device points to a weak commercialisation mechanism of public-science during the period. The initial science that had emerged from a public-science institution was not commercialised by it. Tata independently developed the 'Swach' purifier by developing organisational routines for embedding tacit knowledge brought in by researchers who previously worked at public-science institutions.

Therefore it is likely that weak university-industry links, a weak VC financing system, and a pressing need to meet basic needs of people led to a focus on a simpler low-risk silver nanotechnology based solution in the design of Tata Swach. It is also expedient for firms to ensure that low-risk technology research is exploited, because commercial successes of low-cost solutions could help catalyse innovation around more advanced technologies (Singh, 2011)

Moreover, when Swach was launched, Tata Chemicals focus also appears to be to provide consumers their right to clean water given failures in public policy (Iyer, 2009; Sharma & Nupur, 2012), and set aside commercial returns for longer term (AFP, 2009). This may suggest that firms such as Tata who have the resources and reputational advantage can increase their strategic commitments in shaping their institutional environment (Cheng, Zuzul, Jones, & Khanna, 2017). Companies and institutions may not always be mutually exclusive and elements of the state and the private sector can morph into each other (Dieleman & Sachs, 2008). It can therefore be argued that firms such as Tata who wield enormous local influence can be regarded as a national institution. While resources and reputational advantage can help firms in overcoming institutional voids, filling an institutional void can enhance reputational advantage.

Besides, a firm that fills a void will not only gain consumers attention, but also democratise innovation by encouraging other firms to find better solutions and play a more active role in generating and diffusing innovation (Iyer, 2009; Murray, 2011; PTI, 2011). It may also promote entrepreneurial and commercialisation activities in the public-science system, ultimately strengthening institutions by increasing firms access to external scientific and technological input and appropriating value from them into innovative output.

Tata's competitor, Eureka Forbes however licensed a nanotechnology intellectual property on a new 'material' from another public-science institution 'Indian Institute of Technology Madras (IITM)' in 2004 in order to remove pesticides. Though it had introduced the technology in some of its products, and claimed to be the first nanotechnology based water filter (Murali, 2007), the products were not targeted for base-of-pyramid income groups, because the production could not be scaled to bring down the costs (Singh, 2008). Moreover the filter was used as a retrofit on its existing products to additionally remove pesticides (Jayaraman, 2007). Subsequently IITM created a spin-off business 'InnoNano Research' (INR) in 2008 to produce a non-electric water-purifier based on new nano-materials it had been developing to capture ions like arsenic, iron and fluorides, and effectively kill microorganisms, and also make affordable water filters for base-of-pyramid that can tackle complex water problems (Gravotta, 2013; Kumar, et al., 2016; Pradeep & Anshup, 2009).

The main investigator at IITM, Prof. Pradeep, has received research support from the governments Department of Science and Technology (DST) which also supported a 'Thematic unit of excellence in Water purification'. After many pilot studies, it was only in 2016 that a US based VC firm Nanoholdings plc acquired InnoNano for $18 million (Rs 1.2 billion) (Prasad, 2016) and formed a separate company headquartered in Singapore, 'Safewater Nano pte', to globally commercialise its water purifier that can effectively tackle complex water problems and remove metal ions, fluorides and bacteria without requiring any electricity. Nanoholdings plc had also previously for four years supported InnoNano's global patenting activity before the acquisition. InnoNano's water filter is called AMRIT, which literally means nectar in Hindi language, is also an abbreviation for Arsenic and Metal ion Removal using Indian Technology. The unit costs $16 and can provide clean water for an impoverished family for an entire year (Gravotta, 2013; Janin, 2016).

It appears that IITM was able to lead 'new materials' research for water purification, because state funded research in India, especially in 'basic R&D', is mostly allocated to a handful of elite research universities and institutes (Varma, 2014). In the best public-science institutions such as the various IIT's in India, they not only recruit the best academic staff and students, but the academic staff are likely to remain in them for most of their scientific careers because of their ability to attract resources and funding for research due to the elite status of their institutions. Interestingly, elite research institutions such as the IIT's were created with on-campus housing to support research staff careers.

Further, a recently announced Prime Minsters Research Fellowship (PMRF) (Sanghi, 2018), which adds a significant increase to research funding in India, confirms this disparity. PMRF is targeted at attracting the best students from a small select group of about 60 higher education institutions to a handful of 17 elite research institutions. I argue that, when public-science and industry links are weak and local venture finance mechanisms are also weak, policies that are not highly competitive in distributing public funds to researchers in public-science organisations and mostly handed to elite institutions, may not encourage research efficiency in finding novel yet lowest-cost technological solutions in the shorter term for pressing issues such as access to clean water. Additionally, according to Prof. Murali Sastry, "*issues around accessibility and distribution of funding not only exists for lab research, but also in the government's various recent venture funding mechanisms (including soft-loans) for scaling-up scientific output. This ecosystem is evolving with the emergence of VC and Angel Investor firms.*"

Notably, though the team at IITM initially received funding for pilot studies to test the product, however lack of necessary venture finance during seed stages of commercialisation and industry support for scale-up hindered the speed of commercialisation. This is also presumably because the commercial prospects of inventing completely ‘New’ materials are uncertain and take longer time, unlike Tata’s effort to find the right chemistry to bind nano-Silver to RHA in an existing rudimentary device. InnoNano was created five years after the research efforts started in 2003, however it took another eight years since InnoNano before it received any significant venture backing, that too from a non-local VC firm.

Further, the PoU water purification market is very competitive in India, and the lack of uptake by the incumbent players may be due to both the technical and market uncertainty of ‘new materials’. Even for incumbent firms such as Tata and Eureka Forbes, resolving technological uncertainty requires a high level of investment over a long period of time because of pilot plants and process innovation required to meet economies of scale. Moreover in a highly competitive PoU water market, trialability will require a full working system and even then consumers may not be able to easily observe the new technology as regards its universal attributes to remove metal ions, fluorides and microorganisms. In addition, despite its universal attributes, targeting many different developing country markets may require different designs because of different consumer attitudes and design familiarity.

Thus given the long gestation period of advanced nano-materials R&D, it may be challenging to deliver the water purification system at low-cost for consumers without significant initial investment and being patient about a long period for return on investment. In addition, unlike the case of the rudimentary Sujal device that needed an incremental nanotechnology solution and for which Tata Chemicals recruited experienced academic researchers, firms rarely have an interest in actively engaging with academic researchers conducting generic research with potentially radical outcomes given the risks involved. Though Prof. Pradeep says that “ *firms who earlier came to me for a short three month problem solving project are willing to commit* *now for five years and also fund 20-30% of equipment costs",* however he also admits that *" this is not true across the system and limited to very few academics*". If firms engage with public-science institutions on a larger scale, it can reduce costs of undertaking research and encourage integration of new transformational knowledge into firm's capabilities, thus leading to faster diffusion of radical low-cost solutions.

Both our interviewees also admit that in general, the appetite of firms to recruit senior researchers from academic institutions is weak in materials science based industry. Moreover, if they have to recruit them even for incremental solutions such as in the case of Tata Chemicals, it indicates a weak absorptive capacity of firms and this could also explain the lack of active engagement with academic researchers working in more remote areas.

Tata Chemicals now not only sells a few variants of the original non-electric Swach purifier, but it also produces an electric variant that is not targeted at the low income consumer. Moreover the electric variant combines other existing technologies with its own silver impregnation technology. Though Tata's strategic choice to start with an offer to the low income consumers may have made it appear more innovative, and sometimes the original Swach has been referred to as market disruptive, it appears that it hasn't engaged in more advanced materials development that can solve multiple water quality problems at low cost, and it has rather diversified into offering a higher priced product not targeted for the low income groups.

An analysis of Tata's water purification patents since early publications in 2010 until May 2018 reveals 27 patent families, however the number of granted patent families is only 2 till date (one each in year 2014 and 2015). Further looking at patenting activity (families) by priority or grant year in figure 2, most patenting activity was in the three years between 2010 and 2012 (16 families) just after the release of Tata Swach in Dec 2009, and there have only been 11 patents in the five years since 2012. Further, since 2012, the patenting activity has shown a downward trend. Moreover, there has only been one Patent family on heavy metal (Arsenic) removal in 2012, which has still not been granted.

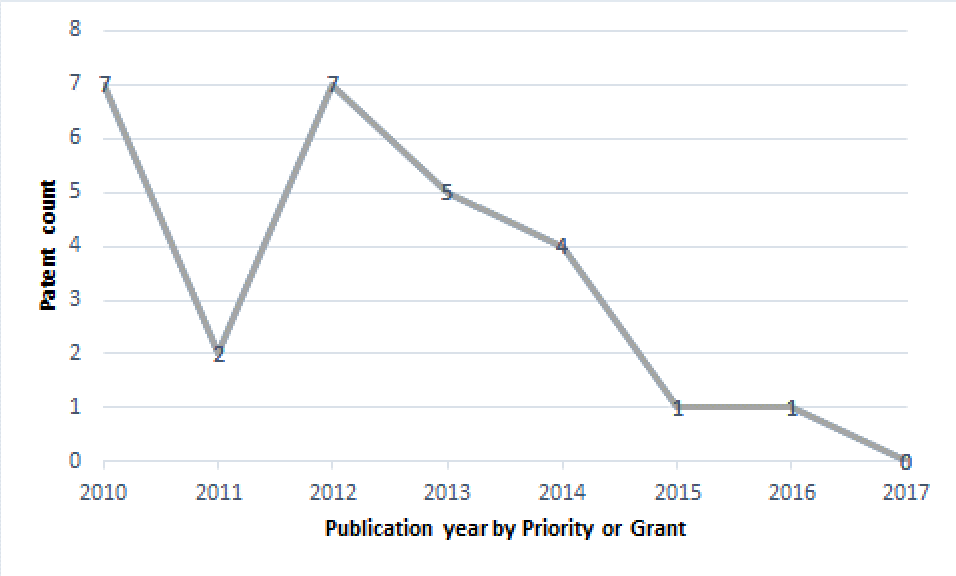


Figure 2: Analysis of Tata's Patents related to Point of Use Water Purification

The above patenting trend may possibly be a result of weak innovation capability of firms due to lack of engagement with academics working in more remote areas, taking into observation the fact that Prof. Murali Sastry had also left Tata Chemicals around 2011. In the article by Singh (2011), Sastry alludes that there is considerable scope for new materials given the success of Swach. Further, Singh (2011) and Subbu (2009) affirm that Tata chemicals was testing attachments that can remove arsenic and fluoride, and a version of Swach would soon carry such attachments. However, patenting activity and Tata's current product offerings do not confirm commercialisation of these efforts.

Tellis, et al. (2009) who surveyed firms in 17 emerging countries including India, argue that national drivers are unlikely to be major discriminators of a firm's performance and corporate culture is important for radical innovation. I agree that 'Corporate culture' is significant, which in the current context entails engaging leading academic researchers in ‘New’ materials innovation in order to cannibalize legacy products and demonstrate future market orientation. However, I also argue that when public funding mechanisms in fundamental R&D favours a handful of elite research institutions, firms have limited opportunity for engagement.

Though in 2007, Tata setup the “Tata Group Innovation Forum” (TGIF) to leverage internal resources and skills (Bhandari, 2013), and engaged leading academics from elite Business schools as consultants and advisors, however recently in 2016 Tata group entered into alliances with elite public-science Institutions globally (Mendonca & Sengupta, 2016). It has set aside £25m to fund cutting edge research, including in advanced materials, at Harvard and Yale Universities in the US, and also send its researchers for training. In India, Tata steel has recently setup the ‘Tata Steel Advanced Materials Research Centre” (TSAMRC) at IITM in 2017, which will initially be developing new materials for green energy and light-weighting applications (The Avenue Mail, 2017). It appears that there is willingness for gaining novel research skills in ‘new’ materials from the public-science base and although it is early days, yet when engagement is limited in size and scope to a few elite research institutions, firms may find it difficult to change their innovative competencies in the short to medium term. Nonetheless, the recent efforts by Tata does not disclaim my specific observations around Tata Chemicals innovations in PoU water purification during the observed period, nor does it affect my general examination of broader institutional features.

Conclusions and Implications

Previous literature has focused on ‘how’ BYD’s success is a result of its capability to reengineer a new process for making rechargeable LIBs in response to market needs and size (Quan, et al., 2017; Rao, 2013; Williamson, 2010; Zeschky, et al., 2014). Further, previous literature also suggests that the development of distinctive low-cost capabilities at BYD was a result of sourcing technological knowledge externally and developing new organisational routines and production processes by coordinating with partners (Fishman, 2005, p. 215). It is therefore not hyperbole to infer that previous studies have largely ignored institutional drivers. I have argued that such low-cost 'incremental' innovation capabilities were primarily a result of Chinas earlier diffusion oriented policies for producing scientific and technical labour without advanced research skills. Further weak university-industry links meant that engagement was normally restricted to solving short-term problems, and Chinese firms had to therefore rely on outside MNC's for developing their distinctive capabilities.

BYD's current strategy appears to be to reinforce its core low-cost capabilities in LIBs through diversifying into applications such as automobiles. This is presumably due to Chinese governments focus on supporting scaling-up of existing technologies in priority economic sectors which is in contest with its policy on enhancing endogenous innovation capability. Moreover, though the stated aims of CRI are to research on 'new materials' and become a prime R&D centre nationally and globally, I do not find patenting evidence of active strategic investments in 'new battery technology' in the last two decades, and data suggests that most focus has been improvements to existing LIB technologies.

Despite the creation of innovation centres such as CICCSE to bolster national capability in advanced research, industrial engagement appears to be in solving current problems and I did not find evidence of active support for commercial development of remote technologies. Even if public-science institutions are engaged with industry, unless firms make strategic R&D investments and recruit leading researchers from universities, engagement is likely to be in solving current problems within the governments priority sectors, rather than in 'generic' and ‘pre-competitive’ areas even though they hold potential for newer and higher performance technologies at lower cost like Sodium-Carbon dioxide batteries at CICCSE. I therefore find inconsistencies in both current firm level strategy and national policy level that would hinder development of radical low-cost innovation in new battery technologies in China.

In the case of Tata, previous literature suggests that the large consumer demand for a low-cost water purification solution for the BoP income group was the primary reason for Tata’s response in the form of Swach (Tiwari & Herstatt, 2012). Further, previous literature also suggests that frugal innovation does not mean low-tech or cheaper versions of existing technologies, and that innovations such as Tata Swach combine low-tech with high-tech (Bound & Thornton, 2012; Wooldridge, 2012). I have argued that the technology in Tata Swach is not high-tech and that Tata’s focus on simpler low-risk nanotechnology is a result of its weak ‘absorptive capacity’. Even for an incremental innovation, Tata needed to recruit leading scientists from public-science institutions who brought in their tacit knowledge, thus indicating a weak ‘absorptive capacity’. Previous literature has therefore largely ignored how institutions, particularly public-science system and firms engagement with them frames low-cost incremental innovation capabilities.

Tata’s initial altruistic mission to provide low-cost and affordable clean-water solutions for BoP suggests that firms such as Tata who have the resources can increase their strategic commitments and come to be regarded as a key institution. However, I find a drift from Tata’s original mission, because it also now offers an electric variant targeted at the higher income group. This implies weak capability for more radical innovation and a lack of engagement with academic researchers working in more remote areas like that at IITM that led to new nano-materials with potential for a low-cost non-electric purifier.

One could however also assume that firms in general have limited opportunities for engagement, because only a handful of elite institutions conduct research in remote areas. Nevertheless, even Tata's competitor in PoU water purification, Eureka Forbes, only licensed a technology from IITM to retrofit onto its existing product offers not targeted at the BoP. IITM had to independently progress a new venture that had a long-gestation before it received any support, that too from a non-local VC firm to globally commercialize innovation around its new nano-materials. In addition to a weak VC system, this may also imply lack of appetite from local firms for highly uncertain research around new materials. Despite our above observation, if one assumes that developmental issues around clean water necessitate shorter term solutions, it is questionable whether distribution of public funds in remote areas to a handful of elite research institutions like the various IITs, and hence a lack of research competition can provide the lowest-cost solutions.

The current largely market based understanding of 'low-cost' innovation does not therefore adequately mirror the more complex reality on institutional drivers and changes. Both the cases illustrate that diffusion oriented policies and weak university-industry links played a critical role in firms low-cost incremental innovations, either by providing technical and scientific labour at low cost as in the case of BYD, or by supplying tacit knowledge through leading academics as in the case of Tata.

However as regards remote and 'pre-competitive' research conducted by the public-science system, with the potential for radical technologies that give better performance at even lower costs, the current structure of institutions and firms strategies may not encourage their commercial development, especially because of a lack of strategic investment in uncertain R&D by incumbent firms. The passive engagement of firms may be due to mission drift caused by lack of sufficient opportunities to engage with the public-science system or because of government support for priority economic sectors. Arguably, institutional changes are resisted more than technological changes (Lastres, 1994), and one would therefore anticipate that the more pervasive and radical are technological changes, the more significant will be changes in public-science institutions and engagement with industry, thus readjusting the entire innovation system to a new form of developing and diffusing technologies.

Since only two cases were examined, further empirical research on competencies of both domestic and foreign firms in ETC's is clearly warranted to confirm our conclusions. The conclusions of this study would be useful to both firms and policy makers, in encouraging institutions to facilitate firms in developing linkages with the public science system. I hope that this study will provide justification for governments in ETC's to balance growth in priority economic sectors with endogenous innovation and in ensuring research efficiency for meeting challenges to pressing problems. Further, I hope that this study will support firms in ETC's to comprehend the paramount need to scale radical innovations emerging from the public-science system. Given the current shifts in the policy of key emerging countries such as the current Indian government's focus on Foreign Direct Investment (FDI) led manufacturing campaign 'Make in India' (Srivastava, 2015), the assumptions and conclusions in this study may be replaced. Nevertheless, this study will hopefully encourage both firms and policy makers in enhancing the overall innovation system. This would lead to a robust business environment that promotes entrepreneurial activities and ultimately increases innovative output at the firm level.

However it should be emphasised that beyond offering directions for practice, the main purpose of this study was to highlight a promising direction for future research that focuses on how firms in ETC's develop distinctive capabilities for low-cost innovation and examine the implications of external learning for radical low-cost innovation. Current literature is focused on demand as a key driver of low-cost Innovation (Herstatt & Tiwari, 2017; Petrick, & Juntiwasarakij, 2011; Radjou, et al., 2012) and some attempt to understand how firms overcome institutional constraints (Bhatti & Ventresca, 2013; Ernst, et al., 2015). The literature is weak in offering a prognosis of how institutions facilitate low-cost innovation in ETC's and what mechanisms are needed to augment capabilities of firms, and hence my research will greatly add to the growing body of knowledge and debate in the field. Many studies in the field are of a conceptual nature attempting to understand the boundaries of various terminologies. This study sheds light on the importance of an underappreciated topic in an under-theorised setting. This study provides a more comprehensive and balanced perspective of both firm level and institutional context of innovation in ETC's. Scholars, managers and government's may gain useful lens and insights on innovation capabilities from this study and extend them in their pursuit of specific academic, managerial strategy and policy efforts in the context of ETC's.

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