Analysis of International Technology Development and Commercialization Policy Instruments and Infrastructures

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The United States emerged from World War II as the dominant technology-driven economy in the world. The development of new technologies benefited from substantial investment in basic science.[1] For decades, this science base was drawn upon to the extent that virtually every major technology with global reach was developed and initially commercialized within the U.S. economy. This was accomplished by an unprecedented combination of government and industry investment in research and development (R&D) coupled with subsequent investment in technology-implementing hardware and software, skilled labor, and a world leading technology-based infrastructure, including top-rated universities and government laboratories.

As a consequence, for three decades after WWII the United States was the dominant leader in

[1] The U.S. still has 79 of the world's top 100 universities in 2018, as ranked by uniRank (*http://www.4icu.org/top-universities-world/*).

science and technology development and subsequent innovation. Although most of this technology was initially developed for specific missions such as national defense and later for space exploration, energy independence, and national health, the resulting "generic technologies" or "technology platforms" eventually were applied to commercial markets.

Without significant competition from a global economy still recovering from WWII, the inefficiency of this indirect and drawn out process of depending on spinoffs from mission-oriented R&D was not burdensome. U.S. jobs, personal incomes, and overall wealth rose steadily, as a range of U.S. developed technologies spurred significant productivity growth.

But, while mission technologies had substantial R&D budgets and large government bureaucracies to manage their development, the Federal Government had and continues to have very little institutionalized technology-based economic development (TBED) policy capability.

The lack of a substantive and comprehensive national innovation policy derives from the U.S. tradition of a laissez-faire approach to developing commercial applications. It was asserted that market opportunity was sufficient to entice risk taking and thus lead to the commercialization of innovative products and services.

This rather simplistic market sufficiency philosophy was not a problem in the absence of significant foreign competition nor was the fact that government R&D and associated infrastructure support were strongly oriented toward social objectives. The U.S. economy has had a strong tradition of entrepreneurial activity, which encouraged risk taking. Coupled with plentiful venture capital, the U.S. economy experienced substantial innovation and subsequent technology-based growth. The rate of growth was further supported by a U.S. educational system that produced a consistently strong pool of skilled workers, including large numbers of immigrants from around the world who contributed significantly to the U.S. advantage in both skilled workers and entrepreneurs.

1. The TBED Policy Deficit

The cost in terms of restrained economic growth of an inadequate TBED policy is due to the fact that today's global technology platforms are increasingly developed elsewhere in the world, creating increasingly severe pressure on domestic industries and supporting infrastructures.

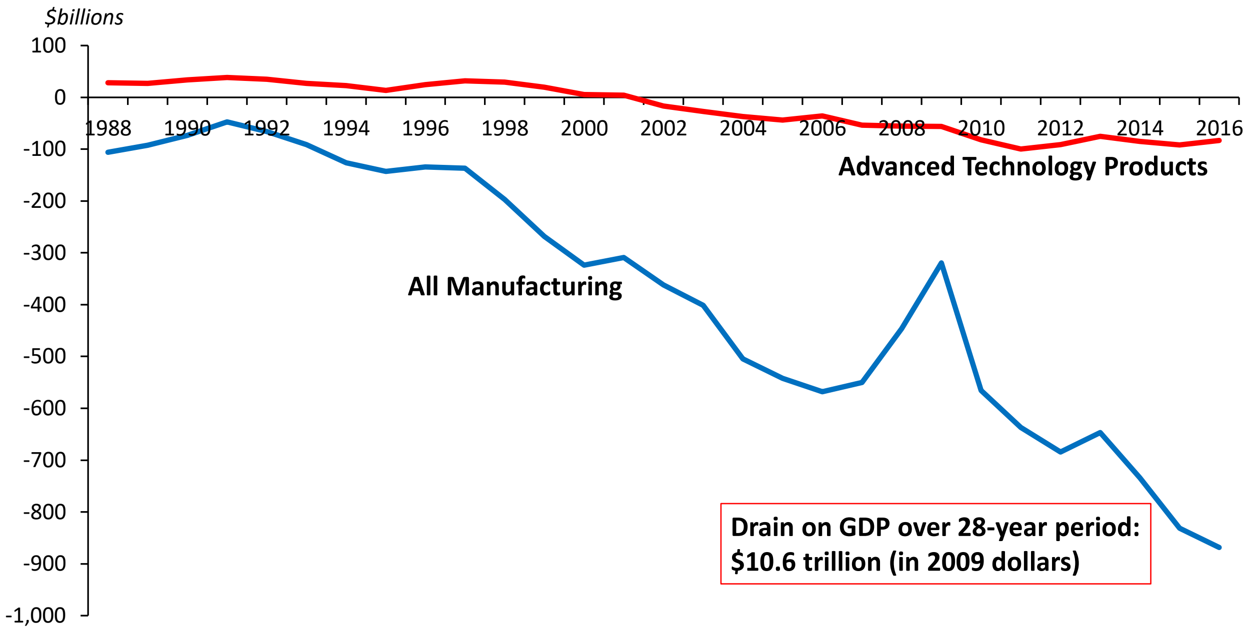
Indicative of restrained U.S. growth is the fact that domestic fixed private investment (FPI) in physical assets such as machinery, land, buildings, installations, vehicles, and technology is too low, and survey after survey of industry managers show that our supply of skilled labor is inadequate. U.S. Government research institutions and R&D budgets are still oriented largely toward a set of social objectives such as defense and public health that only indirectly leverage economic growth. At the same time, other economies have focused largely on optimizing their R&D investment to maximize the growth of their domestic economies.

The negative economic impact has been pronounced. For the first 30 years after World War II (1948-1978), when the United States was the dominant technology-driven and thus the highest productivity economy, the average annual real growth rate of Gross Domestic Product (GDP) was 3.9%. During the next 30 years, the growth rate dropped to 3.0%, as the effects of globalization began to be felt. Since the 2008 recession, real economic growth has averaged 2.1%, and the Federal Reserve forecasts the growth rate to remain at around 2% for the foreseeable future. Thus, the U.S. economy is expanding at half its post-WWII pace.

One component of GDP that deserves special attention is household income, as it is the single largest source of demand. In 2016, U.S. real median household income ($59,039) finally exceeded the level reached nine years earlier in 2007, just before the Great Recession. Many analysts have characterized this event as encouraging, but the reality is that in addition to taking too long to occur as a cyclical rebound, this important income measure has barely nudged above the 1999 peak of $58,665. In other words, in the past 17 years, real household income has been flat.

By far the most important policy issue for long-term domestic economic growth is the fact that China, South Korea, and other Asian nations have raised their productivities steadily for several

Fig. 1 ***Trade Balances in "Advanced Technology Products" and All Manufacturing: 1988-2016***



Source: Census Bureau

decades. This makes their exports increasingly competitive on their own merits. Thus, even if all trade barriers are removed, an economy still has to develop competitive products and services to grow.

As described in detail in this paper, a major global shift is occurring away from the U.S. economic growth model of laissez-faire economic growth policy toward a "public-private investment" model that more efficiently supports technology-based economic development (TBED). The key attribute of this growth model is cooperative and coordinated investment by the public and private sectors.

Further, this model is being implemented to an increasing extent on a regional basis to promote competitive differentiation and to capture co-location synergies. However, the aggregate impact of the collective advancement of competitor TBED policies in Europe and Asia is seen in the long-term decline in U.S. trade competitiveness, as demonstrated in *Fig.1*.

As described in Tassey (2018b), TBED policies are a complex set of public and private investments. This stands in contrast to traditional U.S. technology-based economic growth policy in which the only frequently mentioned metric driving "innovation policy" was R&D intensity.

R&D intensity is certainly correlated with per capita GDP, but this summary statistic ignores a wide range of financial and institutional policies that determine the efficiency of R&D spending and thereby the rate of productivity growth and ultimately GDP growth.

Even so, it remains a an important summary indicator of an economies investment in technology as the means of competing in the global economy. As Table 1 shows, the U.S. economy has not kept up with its major competitors. Thus, R&D efficiency issues aside, the American economy is not responding to globalization.

Table 1 **Comparative Growth Rates in National R&D Intensity**

	United States	France	Germany	U.K.	China	Japan	South Korea
% Change 1991-2015	5.0%	-4.3%	18.6%	16.3%	183.6%	13.8%	135.0%

Source: OECD, M*ain Science and Technology Indicators/Country R&D Intensities, 2015*

Moreover, even with a high R&D intensity, many steps and a complex set of investments and institutional resources are required to compete in the increasingly technology driven global economy where competing economies are investing aggressively in the range of public and private assets that create a modern, competitive innovation ecosystem.

Having a leading university system that produces advances in basic science is a prerequisite for technology-based competitiveness. However, the complexity of successfully developing and commercializing new technologies requires a complex set of institutional and private sector investments. Each stage of the evolution of a technology's life cycle is dependent on unique sets of public and private assets.

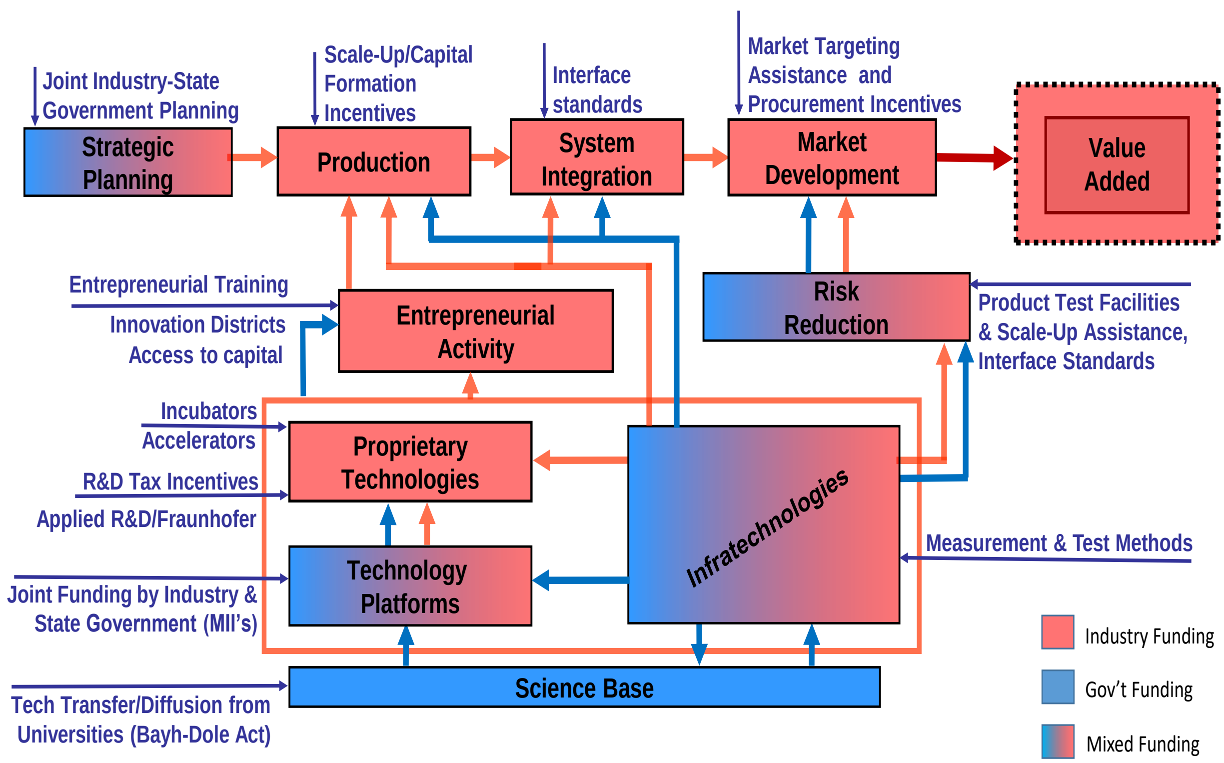
For example, Parilla *et al* (2015) argue that "U.S. manufacturers are often unable to bridge the 'valley of death' between the basic research phase and industrial production due to lack of capital and other key resources." The valley-of-death label results from the fact that the increasing complexity of modern science does not allow a direct transition to the applied R&D, which produces the technologies that drive innovation.

The result of this critical "transition phase" of R&D between science and the development of proprietary technologies are the quasi-public "technology platforms" that prove technological concepts and hence reduce technical and market risk sufficiently to allow positive corporate decision making with respect to undertaking the substantial applied R&D that produces the market ready "proprietary technologies". The valley of death will widen without effective support for pre-competitive technology research that produces the technology platforms enabling the subsequent and much larger proprietary research performed in corporate laboratories.

2. *The Technology Element Model as a Basis for TBED Policies*

Recognizing the existence of this evolutionary process, industrialized nations have increased investment in domestic ecosystems based on the a "technology element model (TEM)" depicted

Fig. 2 **TBED Policy Tools Across the Technology Life Cycle**



Based on Tassey (2007, 2010, 2014)

in *Fig. 2*. This model provides the necessary framework for TBED policies aimed at specific phases of the evolutionary development and commercialization of new technologies. Therefore, a brief description is presented here to provide the framework for discussion of specific TBED policies.

The TEM indicates the development and commercialization sequence (arrows) of the typical modern industrial technology and also characterizes the various elements in terms of their public-good content (colors) and hence the appropriate role for government in support of each element.

Governments around the world are expanding investment across this range of technology elements, as described in the following sections. The policy objective is to capture maximum value added for their economies by developing a domestic science base and integrating the university sourcing of this science with subsequent industry technology platform development. Once a new platform is developed, a second set of TBED policies are implemented to support the applied R&D that leads directly to commercialization and market penetration, and, in so doing, achieve maximum valued added for their domestic economies.

The cross-cutting policy principle in the face of rapidly expanding and increasingly sophisticated TBED policy structures across the global economy is a focus on increasing R&D efficiency (and, more broadly, innovation efficiency) by integrating public and private research, technology development, and commercialization assets in an integrated innovation ecosystem.

That is, the policy imperative is to implement comprehensive "public-private asset" economic growth policies, which means focusing on investment in the range of public and private economic assets that produce sustained high rates of productivity growth.

Such investment is how the U.S. rose to become the world's leading economy. Unfortunately, Americans are poor students of their economic history. The last trade surplus for the U.S. in goods was in 1975, so it is hard to blame the Chinese or the South Koreans in the last two decades or the Japanese and Germans in the past four decades, as well as other nations who have increased their productivity and hence competitiveness. Our denial of the need to invest in sufficient productivity growth to successfully compete in global markets over time has resulted in inadequate export growth in higher value-added products and increased susceptibility to import competition with the result of virtually stagnant real incomes.

> "For the country to seize on manufacturing's recent momentum, however, it must rebuild what Harvard Business School researchers Gary Pisano and Willy Shih (2012) call the 'industrial commons'—the concentrations of research institutions, skilled workers, and suppliers that form the backbone of America's most competitive industrial hubs. Manufacturers thrive when they draw on the collective knowledge and spillovers from clusters of similar firms and deep pools of labor, which in turn are anchored by supportive institutions such as universities, research institutes, community colleges, and industry consortiums.[5] These networks, which concentrate in regional economies, are together responsible for the key driver of industrial competitiveness: a highly trained workforce that can use technology to translate basic and applied research and development (R&D) to large-scale commercial innovations" (Parilla *et al*, 2015).

In responding to these policy imperatives, it is also essential to incorporate fundamental trends in the nature of technology. An OECD (2015a) report succinctly states the general trend driving current innovation policy:

> "Today in many OECD countries, firms invest as much in the knowledge-based capital (KBC) that drives innovation, such as software, databases, research and

> development, firm-specific skills and organizational capital, as they do in physical assets, such as machinery, equipment or buildings."

Policy analysts may respond that of course that is the case. However, when TBED policies around the world are examined, one finds that implementation strategies vary significantly in terms of both size and scope. The following sections describe the different TBED policy structures economies have been chosen to achieve successful innovation and subsequent global market penetration. The technology element model will be used to indicate specific policy targets and the consequent stimulation of knowledge production and subsequent knowledge flows downstream economic activity.

3. Applying the Technology Element Model to Global TBED Policies

The complex and dynamic character of modern technologies require each TBED policy instrument to be implemented at the appropriate stage of the technology's life cycle and done so in an integrative mode with adjacent phases of the target technology's life cycle. The specific policy content and timing are determined by the nature of the target technology and hence its evolutionary development path. That is, the technology elements and their associated investment requirements, as depicted in *Fig. 2*, will evolve along a specific expansion path to produce economic benefits.

All modern technologies originate from advances in science, produced largely by universities. In the past, such knowledge slowly and inefficiently diffused into industry where technological applications were developed. Realizing the barrier to technology development and commercialization that this inefficient process imparts, countries are providing stronger incentives to universities to promote and even participate in technology development in cooperation with domestic firms. As discussed in the next section, most economies have responded by implementing a range of university IP management policies and, equally important, support for actual technology development.

However, results have been mixed, which has stimulated governments around the world to address both the complexity and the evolutionary nature of TBED. The development and commercialization of new technologies requires cooperation/partnering among a range of suppliers of specific technology elements. Some countries, such as China, are investing in mammoth "innovation hubs" in an attempt to capture economies of scale and especially economies of scope. Others, especially European economies, are promoting a relatively larger number of smaller clusters. The U.S., with its traditional laissez-faire approach to innovation policy, has a diverse range of clusters, which have resulted from independent state initiatives.

As long as this "experimental" approach by the U.S. is monitored and analyzed, and lessons learned applied across all regional economies, it could be the best overall strategy. However, as the discussion in this paper shows, not enough is known about scale and scope effects, as well as timing of application. Some older and now large innovation clusters (alternatively, "hubs," "districts," or "orchards," as such agglomerations of technology assets are now called) have demonstrated better economic performance than others. So, policymakers need to know what factors determine success.

TBED investment policy assessments are further complicated by the fact that in addition to the categories of economic assets underpinning regional TBED "clusters" that have significant private-good content, the complex technical infrastructure that supports high-tech supply chains and has considerable public-good content must be planned for and supplied beginning early in the implementation of a region's growth strategy. Such infrastructure not only provides technical support to individual private companies but also provides integration infrastructure assistance to enable migration of technical knowledge among these companies.[2]

More generally, the complexity of today's technologies and their changing nature as development proceeds, especially their public-good content, requires a number of different policy instruments—each one tailored to the nature of the investment activity at a particular phase in the technology's development.

The correct policy structure is determined by the nature of industrial technologies and hence their evolutionary development path. In this regard, *Fig. 2* depicts the elements of an industrial technology and the order in which they typically evolve to produce commercial success. For each element, the public-good content is indicated by the blue shading, while red shading represents private-good content.

The subsequent process of transforming science into technology and eventually innovation is characterized in *Fig. 2* by the arrows, which show the flow of progressively more applied technical knowledge (upward in the diagram) until commercialization occurs.

Thus, science is first used to create "technology platforms," which provide the proof of concept necessary to allow industry to rationalize the substantial investment in applied R&D that eventually creates innovative products and services. This proof-of-concept research, by virtue of occurring early in the R&D cycle and having a range of potential commercial applications well beyond the set of target markets of even large R&D-intensive companies demands a public-private cooperative approach to conducting such research.

The end point of crossing of the "valley of death" is a "technology concept model" or "technology platform," as it is labeled in *Fig. 2* (Tassey, 2007, 2014). This "proof of concept," as the R&D management literature calls it, is extremely important in facilitating the much larger later-phase R&D investment (largely undertaken with private funding). Because of the collective (industry-wide) use of technology platforms, direct participation of industry in the research

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[2] The term "technical infrastructure" encompasses a wide range of materials properties data, measurement and testing techniques, process and quality control methods, and market transaction (product acceptance testing) protocols. Many of these "infratechnologies" are provided by NIST and end up as industry standards. The semiconductor industry, for example, has over 1,000 standards, without which it could not function. See Tassey (2014, 2017b).

process facilitates early and more efficient in applied R&D that eventually produces innovations.

Even after applied R&D is initiated within individual companies, the complexity of today's R&D requires access to external (to the firm) resources, such as the research consortium that developed the technology platform, including the university participant. Such interactions are more efficient when the parties involved are co-located (i.e., within an innovation cluster) due to the tacit nature of early-phase technical knowledge.

A critical policy consequence of such systematic government funding of early-phase technology development is that the multi-phase evolution of a modern technology's development explains why the innovation cluster concept has become so important. It brings public and private resources together to allow "risk pooling" and the assimilation of complementary public and private research assets that can only be provided by a combination of private companies and public research assets typically found in universities and government laboratories. Silicon Valley has prospered because it evolved somewhat serendipitously from having both categories of assets in the same geographic region.

Another important factor in TBED cluster formation is the fact that the early phases of a technology's development produce complex knowledge that has a tacit character, as opposed to the more codified character of applied technology produced in the later phases of the R&D cycle. Such knowledge passes more readily through person-to-person contact (Tassey, 2007).

Thus, the roles of industry and government and the needed policy support change over a technology's life cycle. This fact means the TBED planners must not only construct effective policy mechanisms but also impose a dynamic management overlay to adjust the use each policy mechanism over a technology's life cycle.

4. Protection and Allocation of University Intellectual Property

The Bayh-Doyle Act of 1980 was a major policy change for the relationship between U.S. government-funded research at universities and subsequent use of this research by domestic firms in innovation efforts. The Act requires universities to file for patents when appropriate from such research, as a first step in created IP that could be efficiently transferred to industry. The result has been a significant impact on the rate and direction of innovative activity. The efficiency potential of such a knowledge diffusion mechanism has not been lost on other governments. However, as described below, different approaches have been taken with different degrees of impact.

University Research and Intellectual Property

All modern technologies originate from advances in science, produced largely by universities. In the past, such knowledge slowly and inefficiently diffused into industry where technological applications were developed. Realizing the barrier to technology development and commercialization that this inefficient process imparted, Congress passed the Bayh-Dole Act in 1980 to provide stronger incentives to universities to promote follow-on technology development investment. As discussed in the next section, this action has had mixed results.

Increasingly intense global competition and the growing complexity of science and the new technologies based on it have forced national governments to improve their overall innovation infrastructure to provide more efficient mechanisms for drawing upon new scientific discoveries to develop new technology platforms with large economic growth potential.

While the processes by which knowledge is transferred through patents are affected by numerous factors, a dominant one is the ownership of the intellectual property rights (IPR) from research results. Who owns a patent has a "gate keeper" effect on the potential for eventual commercialization, as different types of owners will have different incentives to attempt or facilitate the investment required to turn the IP into technology with commercial value.

Over the past three decades, most European countries have moved away from inventor ownership of patent rights towards different systems of institutional ownership (Geuna and Rossi, 2011). This trend is a reaction to the earlier passage in the United States of the Bayh-Dole Act. In fact, a good portion of Europe's major economies now allow universities to retain IPR on inventions resulting from government-funded research.[3]

In all of these economies, the emphasis on universities owning the intellectual property (IP) from government-funded research has created a "huge opportunity" for local innovation derived from a regional cluster's university IP. The policy metric used is increases in the number of technological innovations developed as a result of licenses issued by a university to local small firms, many of which were spinoffs from the university stimulated by IP ownership. German-speaking and Scandinavian countries were slower to convert to university ownership of IP (Geuna and Rossi, 2011).[4]

However, although most western industrialized economies' IPR policies now specify institutional ownership, these policies are implemented in a number of forms characterized by differences such as

(1) Specific national laws (public research acts or similar) or by default (i.e. through general laws on IPR ownership). In some cases, non-binding national codes of practice have been formulated to provide guidance to universities.

(2) How the rights are vested in the university. For example, under the "pre-emption rights" principle, the researcher is the first owner of the invention unless the university "claims" the invention within a specified period of time. In the event that the invention is not claimed

[3] Only two countries, Italy and Sweden, continue to maintain systems primarily centered on assigning IPR ownership to the inventor.

[4] OECD's "The Innovation Policy Platform" has a comprehensive treatment of IPR and various systems for managing them (https://www.innovationpolicyplatform.org/content/processes-and-contributions-ip-systems-innovation?topic-filters=12164).

within that period, the IPR remain with the inventor.

(3) The institutional form of the research, which can affect the ownership. Such forms include (a) "contract research", under which IPR are automatically are assigned to the institution, (b) "open research" (wholly university funded, where there is an agreement with external sponsors to consider the research "open" in that rights belong to the inventor and the institution can acquire them only if the inventor does not intend to use or publish them), (c) "service inventions" (from an employee's activity) or "free inventions" (rights are assigned to the inventor and the institution who can commercialize them under a non-exclusive license).[5]

Rigby and Ramlogan (2012, pp. 21-22) summarize interesting data compiled by Australia's National Survey of Research Commercialization showing the returns on investment in technology licensing income, including income from licenses, options, and assignments as a percentage of research spending in Australia, North America and Europe from 2000 to 2009.

The data show a substantial disparity between the licensing incomes of U.S. universities relative to research funding and the same ratio in other countries. The U.S. average ratio for all U.S. universities is 4.7 %. Australia's returns were quite variable over the years due a small sample (for example, its 2009 high was determined by one patent that generated the majority of the country's 2009 income. The Canadian results show a gradual decline from a peak of 2.3% in 2001 to 1.1% in 2008, while the U.K. has shown a gradually increase from a low base of 0.6% in 2000 to 2.1 % in 2008.

Rigby and Ramlogan state that the contrasting performance between Europe and the U.S. has given rise to considerable policy discussion at the European Commission level about the so-called "European paradox," referring to the perceived failure of EU policies to effectively translate scientific advances into commercially viable technologies.

However, they also point to research, which shows that when distinguishing between university owned and university invented patents, the perceived gap between the U.S. and Europe university patent production is much smaller. Specifically, Crespi *et al* (2007) find that, on average for six countries studied, two-thirds of the patents with at least one university inventor are not owned by universities. Lissoni et al.(2008) show a similar result from a study of France, Italy, and Sweden. The conclusion is that European universities may actually contribute as much technical knowledge as their American counterparts; it is just that they are less likely to claim ownership of the IP.

Finally, Rigby and Ramlogan cite a study by Conti & Gaule (2011) that uses licensing data to assess whether U.S. technology transfer offices (TTOs) have outperformed their European equivalents in negotiating license agreements or earning license revenue. Using explanatory

[5] Adapted from Geuna and Rossi (2011). See pp. 11-12 for more detail.

variables such as quality of academic institutions, their research orientation, number of publications, demand for technology, TTO staffing levels and experience, the authors determined that, in terms of licensing revenue, European TTOs performed as well as their U.S. counterparts with respect to number of licenses but earned significantly less revenue.

The study determined that the reason for the licensing revenue differential is that "U.S. TTOs were more focused on generating revenue relative to other objectives such as local development and faculty service." Moreover, they employed more staff with industry experience that likely meant greater experience at negotiating the financial clauses of licensing contracts.

Clearly, IPR management is a complicated policy tool and needs constant review and adjustment to maximize TBED. And, this complexity is accentuated by the fact that across European countries, legislative frameworks regulating academic patenting are often weak, leaving, for example, most European universities to define their own internal IPR management policies.

Nevertheless, Geuna and Rossi (2011) cite data from the Eurostat Science and Technology database, which show that most countries achieved a remarkable increase in university patenting in response to the shift to university IP ownership, with patent output in the EU-27 doubling between the late 1990s and the mid-2000s.

They also point out that patenting was just one of a number of expansions/upgrades to national economic growth strategies. In fact, all European countries have instituted broader sets of TBED policies. For example, in the U.K. support for entrepreneurial activities in universities began to increase in the mid-1980s, which was a natural complementary policy focus to the establishment of technology transfer offices (Meyer and Tang, 2007). In fact, by the mid-1990s, government financial support for entrepreneurial activity had become widespread across Europe. For example, in Germany, the switch to institutional ownership of academic IPR was complemented by substantial federal subsidies for regional patent exploitation institutions (Geuna and Rossi, 2011).

Similarly, in Norway the switch to institutional ownership of IP was accompanied by the setting up of a technology transfer infrastructure composed of university TTO's, with actual utilization of new technologies supported by seed capital funding, mostly provided by government (Iversen, Gulbrandsen and Klitkou, 2007). The Danish government also provided substantial funding for the creation of a technology transfer infrastructure following the introduction of institutional ownership (Lissoni et al, 2009).

In Sweden, numerous organizations to support technology transfer were established in the 1990s. Specifically, a series of technology bridging foundations were founded to help universities build links with industry and other stakeholders; science parks were established with public funding; national competence centers were financed jointly by industry, universities and government; and, universities set up their own TTO's (*The Economist*, 2018).

The policy observation from this discussion is the broad adoption across industrialized nations of IPR management tools and, even more important, specific institutionalized functions to promote economic use of the IP. However, such efficiency improvements in IP management are only the beginning of the public-private asset model's policy tools to enhance the successive development and eventual commercialization of new technologies. Collectively, these tools constitute the innovation ecosystem that determines the ultimate efficiency of an economy's TBED strategy. The next section discusses the major policy instruments currently being used by regional economies within the context of a national innovation strategy.

5. Global TBED Strategies

The relentless advance of the global technology-based economy is being accompanied by the evolution of a public-private asset policy model, which is driving the selection and use of TBED policy instruments. Individual policy tools target specific underinvestment phenomena, but the collective economic impact will only be substantial over time if these tools are integrated into larger ecosystems that can achieve economies of scope by improving the productivity of all embedded private and public institutions. To this end, traditional and emerging TBED policy instruments are summarized below and their different implementations across national economies are contrasted.

Clusters, Innovation Districts and Tech Hubs

The previous section emphasized direct transfer of knowledge from universities to private firms who attempt to commercialize this knowledge. However, while improving the efficiency of this process is extremely important, long-term innovative economic output requires a much broader ecosystem of private and public institutions to provide a wide array of market applications of new technologies, including eventually high-tech services.

That is, achieving large economic impact requires capturing economies of scope—many market applications from single technology platforms. To this end, new infrastructures such innovation "hubs"/"clusters" and the broader concept of "innovation districts" are integrating university research into broader R&D efforts with IP issues specified early in the R&D cycle by the collective management of the cluster. Such "institutional innovations" are essential to efficiently cross the valley of death and provide the new technology platforms that drive the varied applied R&D efforts and the a subsequent variety of innovations that create profits and worker income growth at a level that creates substantial regional economic impact.[6]

Katz and Wagner (2014) point out that

> "innovation districts are emerging in dozens of cities and metropolitan areas in the United States and abroad and already reflect distinctive typologies and levels of formal planning. Globally, Barcelona, Berlin, London, Medellin, Montreal, Seoul,

[6] See Tassey (2018b) for extended discussion of these policy tools in the U.S. economy.

Stockholm and Toronto all provide examples of evolving districts.

> In the United States, districts are emerging near anchor institutions in the downtowns and midtowns of cities like Atlanta, Baltimore, Buffalo, Cambridge, Cleveland, Detroit, Houston, Philadelphia, Pittsburgh, St. Louis, and San Diego. They are also developing in Boston, Brooklyn, Chicago, Portland, Providence, San Francisco and Seattle where underutilized areas (particularly older industrial areas) are being re-imagined and remade. Still others are taking shape in the transformation of traditional exurban science parks like Research Triangle Park in Raleigh-Durham, which are scrambling to meet demand for more urbanized, vibrant work and living environments."

Tech hubs are similar to Innovation Districts in that they are associated with urban environments. CBINSIGHTS counts seven American cities among the top 25 Tech Hubs. Significantly, whereas CBINSIGHTS (2008) agrees that Silicon Valley is still the dominant tech hub, they project that "Beijing and Shanghai are poised to be the tech hubs of the future. They lead among high-growth hubs for unicorns, mega-rounds, and large exits. Company creation is accelerating".

The TBED strategies of European and Asian tech-based economies are discussed in detail later in this paper. The main point here is that the rest of the world is rapidly expanding investment in "innovation districts," "innovation orchards," "tech hubs," or whatever variant of the generic innovation cluster model one wants to adopt.

Startup Accelerators and Access to Global Markets

A startup accelerator is a policy mechanism for assisting entrepreneurs in the early development of new technologies. As described by Clark (2014), a startup accelerator is an institutional mechanism that provides a young company both technical and management guidance and financial resources to leverage grow in its size and value in order to "accelerate" the initial round of conventional venture financing. Hathaway (2016) characterizes this mechanism as supporting "early-stage, growth-driven companies through education, mentorship, and financing in a fixed-period, cohort-based setting." The typical length of application is 3-6 months.

Cohen (2013) notes that accelerators "usually provide a small amount of seed capital, plus working space. They also offer a plethora of networking opportunities, with both peer ventures and mentors, who might be successful entrepreneurs, program graduates, venture capitalists, angel investors, or even corporate executives."

The role of an accelerator seems to be evolving in many countries. According to *The Economist* (2018), "a perennial complaint about young tech firms in France is that—despite their gifted engineers and smart ideas—few know how to scale up fast enough to interest big investors." This seems to be due to a widespread fear of going global too soon, not only in terms of marketing strategies, but for early-stage financing.

However, a few French startups have engaged with one of the large accelerators, Y Combinator. As an example, Y Combinator helped a young company, Angolia, to take on more risk by looking outside France for business opportunities and to raise capital. As a result, Angolia was able to raise $74 million from a group of investors led by Accel, a London-based venture capital firm.

According to the *Global Accelerator Report*, more than $206M was invested in 11,305 startups across the world in 2016.[7] The United States continues to be the leading country both in terms of startups accelerators and in dollars invested via this mechanism. The U.S.-Canada share was 3269 startups funded at $107,264,392 (Izquierdo *et al*, 2016)

In the previous year, *The Global Accelerator Report 2015* observed that a majority of accelerators across the global economy still intended to follow the traditional "cash-for-equity" model, which involves investing a small amount of seed money in a startup in exchange for an equity share. The typical investment was about $25,000 in exchange for a 5-10 percent equity share (Izquierdo *et al*, 2015).

However, a significant change seems to be occurring in the way accelerators operate. *The Global Accelerator Report 2016* points out that only 33 percent of accelerators now indicate that they will generate revenue from exits in the future, a significant shift from 2015. This shift in the accelerator business model is resulting from the fact that the small number of exits (178 reported in 2016) has proven insufficient to refinance the operations of accelerators. Moreover, exits usually do not occur earlier than three to five years into a startup's lifecycle, thereby delaying realization of cash flows from an accelerator's investments for several years.

Thus, the *Report* notes, nearly all (90.4 percent) of accelerators globally are exploring new models of revenue generation, such as charging for mentorship, subletting office space, hosting events and working with corporations who contribute resources. Revenue from corporations has seen the largest increase among alternative sources. More than half (52.1 percent) of accelerators are at least partially funded by a corporation, and 67.2 percent aim to generate future revenue from services sold to corporations.

6. Specific Country TBED Strategies

The global economy is increasingly driven by investment in technology and the embodiment of the resulting technologies in efficient production systems. Even large economies like the United States must continually upgrade and refresh their investments in technology and the efficiency with which new technologies are deployed.

However, the relentless growth of global technology-based competition from other parts of the global economy is making the required management of continual change within these

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[7] See *Global Accelerator Report 2016*, produced by Gust (gust.com/accelerator reports/2016/global).

economies more difficult. As summarized in this Section, for example, Northern Europe is an advanced region of the global economy with respect to comprehensive TBED policies and levels of implementation, and its economies have relatively long histories of comprehensive innovation strategy development. Yet, these nations are having to expand efforts to upgrade and expand TBED policy instruments to meet the growing competition.

Significant differences exist among nations in the nature and intensity of their TBED investments, which indicates the lack of an understanding of the importance of technology as a critical economic input, but, more important, the political will to reallocate resources toward technology-based economic growth.

Nevertheless, the world's economy is on average moving relentlessly toward increasing reliance on technology. The following provides some examples of the varying scope and depth of national strategies to this end.

<u>Germany</u>

Germany is famous for its technical and engineering prowess. It has invested over decades in a range of high-tech assets, which make its economy particularly competitive within its strategic focus.

As is the case with most economies, Germany has focused on a particular set of industries and on a particular phase of the technology life cycle. Germany's focus has been advanced manufacturing with emphasis on developing a continually competitive portfolio of products based on existing technology platforms As a result, its economy has performed consistently well in established manufacturing industries where its steady incremental change in both product and process technologies has resulted in high rates of productivity growth.

Unlike the United States, which has a decentralized and incomplete national TBED policy structure (many policy initiatives are undertaken by individual states), the German Government plays a central and substantive role in close coordination with German industry to devise and implement TBED policies.

For example, in 2010 the Germans created "High-Tech Strategy 2020" to promote digitalization of manufacturing. It consisted of ten initiatives, including an Industry 4.0 program (similar to IIOT programs in other countries). The goal is not only to maintain German leadership in manufacturing, but also to ensure it is a major supplier of advanced manufacturing technologies going forward. The government has invested approximately $250 million in government and academic research and it facilitates collaborations among government, business, and trade unions to create and manage manufacturing innovation strategies (Dobbs *et al*, 2015).[8]

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[8] Dobbs further point out that the benefits of Industry 4.0 for an industrialized economy depend on ubiquitous connectivity, not only of machinery and systems within the four walls of the factory, but also across the entire

To accomplish its engineering-driven superiority, its educational system turns out highly qualified scientists and engineers as well as middle-skill technical workers trained in apprenticeship programs. The above average skills of German workers allows the economy's companies to pay above average compensation. Another characteristic of the German economy that helps drive its engineering-based innovation is the presence of strong small and mid-sized (mittelstand) companies, many of which are family-owned and known for making long-term investments (Dobbs et al, 2015).

Coupled with an efficient industry structure and a strong education system is a well-conceived government policy infrastructure, which supports the domestic industry through a range of TBED institutions. A comprehensive Brookings analysis of Germany's manufacturing sector (Parilla *et a*l, 2015) identifies the critical policy tool as the use of public-private collaborations to conduct applied research that accelerate and efficiently achieve high and sustained rates of innovation.[9]

This "cluster" strategy is part of a "dual model" with the other part being an entrenched vocational education system to ensure a continual supply of highly trained workers.[10] As a result, Germany with its comprehensive set of public and private institutions that support advanced manufacturing is maintaining consistent trade surpluses, while the U.S. continues to suffer trade deficits.[11]

The Brookings analysis shows that superior performance, including compensation, is reflected in the fact that medium- and high-technology industries account for a larger share of the sector's total output in Germany (58 percent) than in the United States (42 percent). Yet a cross-national comparison reveals that Germany invests only marginally more in public R&D as a share of its economy. The implication is that their more distributed and institutionally diverse support for manufacturing has yielded a more effective TBED policy structure.

More specifically, a distinguishing difference between the German and U.S. TBED strategies is the German emphasis on government support for applied research. The Fraunhofer Institutes are widely recognized as a dominant policy instrument at this phase of the R&D cycle. Their

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manufacturing value chain. Within the plant, connected machinery and sensors to monitor the movement of parts and activities of labor can raise efficiency, including through real-time supply-chain optimization, real-time yield management, and predictive maintenance. This system relies on a continuous flow of data about equipment performance to avoid breakdowns and to schedule maintenance only when needed. Some of the greatest benefits could arise from (1) allowing retailers and even consumers to connect directly to manufacturers and (2) matching excess manufacturing capacity to demand.

[9] Much of the remainder of this section draws upon this excellent analysis.

[10] German vocational training consists of a widely used combination of formal (classroom) education and on-the-job training. See https://www.make-it-in-germany.com/en/for-qualified-professionals/training-learning/training/vocational-training-in-germany-how-does-it-work.

[11] For example, in 2016, the U.S. had a trade deficit of $869 billion, compared to Germany's trade surplus of $322 billion. For the manufacturing sector, the U.S. trade deficit was $667 billion compared to a surplus of $425 billion for Germany (Brookings analysis of United Nations Conference on Trade and Development data).

purpose is to improve the efficiency of drawing upon existing technology platforms to produce applied technologies. To these ends, Germany has established 67 Institutes with 23,000 employees. Most are in Germany, but a few additional institutes are located in other countries, including the United States.

Fraunhofer institutes offer contract R&D services that cover a range of technical-based activities, including market and patent surveys, and feasibility studies to support R&D portfolio decisions. The focus is on applied R&D that produces commercial prototypes, production scale-up assistance—including the design, construction and testing of pilot plants, and even production-stage analysis and testing services.[12]

Each institute has a distinct specialization (applied polymer research, nanoelectronics, etc.) which falls under broader industry sector targets, such as microelectronics, materials and components, biopharmaceuticals, information technology, etc. Approximately 70 percent of Fraunhofer's funding is generated by contracts with industry and public institutions, with state and federal governments contributing the remaining 30 percent. Thus, the actual price to clients includes a subsidy, as the Fraunhofer institutes only charge companies for the direct costs of a project.

Fraunhofer institutes undertake between 6,000 and 8,000 industry projects per year. The size of these projects varies significantly, ranging from less than 1,000 to several million dollars. Smaller client firms, who do not have sufficient in-house capabilities to address a particular technical challenge, will contract with a Fraunhofer institute to perform pre-production research or develop a prototype. At other times, Fraunhofer institutes will simply allow private-sector researchers access to specialized machinery in order to test prototypes and conduct advanced research. Often, Fraunhofer and industrial scientists work hand-in-hand on a project, promoting the mobility of scientists between universities and industry.

Parilla *et al* (2015) conclude that, through these myriad support functions, Fraunhofer institutes have been the most prominent actor in Germany's promotion of firm-level R&D. In addition to supporting individual firms, Fraunhofer institutes help regional clusters develop a unique comparative advantage by establishing industry or technological specializations within individual institutes. Together, these networks form the backbone of a regional innovation ecosystem. However, the Fraunhofer network has also facilitated "long distance" collaborations, which occur when the closest Fraunhofer facility does not have expertise in the technology of interest for a particular firm.

Additionally, the Brookings analysis points out that regional funding facilitates collaboration among universities, other research institutions, and private companies. In Bavaria, the Ministry

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[12] See https://www.igb.fraunhofer.de/en/companies.html and https://www.igb.fraunhofer.de/en/companies/what-does-fraunhofer-do.html. Some early phase proof-of-concept research is also undertaken.

of Economic Affairs, Infrastructure, Transport and Technology provides funds for joint research through programs such as the New Materials Development Program, Microsystem Technologies Program, and Information and Communication Technologies Program.

State governments also provide innovation vouchers to SMEs to support their R&D activities. Such vouchers allow firms to conduct additional research themselves or to redeem the voucher at a research institution of their choosing. The effect of the innovation vouchers is twofold. First, they promote the participation of SMEs in R&D activities that, due to high financial cost and uncertainty on the return of the investment, would not have occurred otherwise. Second, the vouchers also provide additional funding for research institutions, particularly for applied research organizations, to conduct risky research at a lower cost. The state of Bavaria offers innovation vouchers through its Program for the Introduction of Technologies (BayTP), while also offering loans and capital for recently created start-ups in high-tech industries.

Germany has achieved this superior performance through a comprehensive TBED policy structure, as indicated in *Table 2*. The Leibniz Association and Max Planck Society are world class

Table 2 **German Public & Private Research Institutions by Research Focus/Funding Source**
(pub =public funded; prv = private funded)

Basic Research	***Applied Research***
Academies (pub)	Companies/Industrial Research (prv)
Federal Institutions (pub)	Fraunhofer-Gesellschaft (prv/pub)
Helmholtz[13] (pub)	Helmholtz (pub)
Leibniz Association (prv/pub)	Industrial Research Associations (prv)
Max Planck Society (pub)	Lander Institutions (pub)
Research Infrastructures (pub)	Networks & Clusters (prv)
Universities (pub)	Universities (pub)

Source: Parilla *et al* (2015)

basic research organizations. Importantly, several of these institutions are oriented toward supporting economic growth, rather than social objectives, in particular, the Fraunhofer Society. Drawing upon the country's superb research infrastructure, its manufacturing sector squeezes maximum productivity out of each existing technology platform.

Further, their highly developed public-private infrastructure facilities joint planning for future technology life cycles. Germany's joint planning for the advent of the Industrial Internet of Things

[13] The equivalent of the U.S. Department of Energy's National Laboratories.

(IIOT) is a case in point.[14]

OECD data cited by Parilla *et al* (2015, p.7) indicate modest advantages for Germany over the U.S. in total researchers per 1000 workers (8.2 for Germany vs. 8.8 for the U.S.) and R&D intensity (2.98 percent for Germany vs. 2.79 percent for the U.S.). However, the greater R&D intensity of the German economy and the emphasis on applied R&D drive a higher productivity manufacturing economy.

The higher productivity of the German economy is evident in roughly a 30 percent gap in worker compensation between U.S. and German manufacturing workers.[15] The German educational system is definitely a major factor in the German productivity advantage. It strongly focused on producing highly skilled workers, with significant emphasis on education curricula and strong apprentice programs. The well-developed set of public and private research institutions focusing on applied R&D, especially in manufacturing, has led to a substantial advantage in patents per 1,000 researchers of 53 to 39).

The German apprentice system is particularly noteworthy because of its widespread use. German manufacturers do not recoup the cost of training apprentices during the actual apprenticeship. Rather, such a "human capital investment" will pay off as the resulting highly skilled full-time workers yield higher average productivity. Apprenticeships also allow German manufacturers to evaluate young workers before hiring them full-time, thereby reducing the considerable long-term commitment risk inherent in German labor policy (Parilla *et al*, 2015).

In summary, the German education and training system is effective because (1) it first provides young workers with exceptional basic technical training for high-tech industries, which provides a foundation for learning specialized on-the-job skills; (2) the specifications for specific occupational skills are made in the context of best practices in human capital development, with a strong emphasis on active learning and adaptability, and (3) the emphasis on internal company training (through apprentice programs) facilitates adaptation of worker skills to the specialized needs of regional clusters, as well as facilitating adaptation of generic production processes to the needs of an innovation clusters particular technology focus (Parilla *et al*, 2015).

In contrast, U.S. regional innovation clusters rely more on external public educational infrastructure, specifically universities and community colleges to tailor curricula to company needs. However, this approach does not allow the progressive tailoring of worker skills until after full-employment commitment.

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[14] The industrial internet of things (IIoT) is a network of connectivity among machines in multiple industries in a supply chain to enable enhanced management of entire product technology life cycles. This is accomplished by sensors within products installed during production that collect performance data and transmit it over the Internet to external parties, such as the producer of the equipment who use the data to determine maintenance and upgrade requirements.

[15] See https://www.bls.gov/fls/ichccindustry.htm#C.

Overall, Germany's public-private collaborations in technology development and its dual model for worker training are often considered global best practices. Taken together, German TBED policies are implemented by a set of public and private institutions, which work collaboratively to support manufacturing through investment, implementation, and dynamic management of change. Collaboration has become a dominant characteristic of TBED strategies.

Especially, in emerging technologies, most national economies have emphasized collaborative research for creating new technology platforms from which patentable technologies can be derived. For example, Fornahl *et al* (2011) found that R&D subsidies focusing on single German biotech firms do not enhance the performance, while collaborative research subsidies (i.e., subsidies that are granted to joint R&D projects with two or more partners), have positive impact.

The United States has at least one major advantage in establishing regional innovation clusters in that it has 39 of the top universities in the Leiden Impact Rankings vs. zero for Germany. This fact, combined with Germany's focus on orienting its highly skilled labor force, applied research infrastructure, and highly stable industry supply chains, may collectively be a barrier to developing and assimilating radically new manufacturing technologies.

Nevertheless, in a 2012 study of 36 OECD economies, Germany ranked third in proportion of graduates in STEM fields, compared to 33rd position for the United States. More than 800,000 students participated in apprentice programs in the manufacturing sector.[16] This complement to traditional education expands and diversifies the availability of the needed skilled workforce and at least gives Germany many of the tools needed to transition between technology life cycles.

If U.S. TBED policies are systematically broadened to provide adequate investment in the comprehensive set of support mechanisms described in this paper, the German expertise in continual product development and improvement can be matched and also combined with a world-class research infrastructure for developing radically new technologies with superior long-term growth potential. This combination will achieve a high level of competitiveness over successive technology life cycles.

In this regard, the often heard assertion that Manufacturing U.S.A is a direct imitation of Fraunhofer institutes is incorrect. The MII's focus on an earlier phase of R&D (proof-of-concept or technology platform development for emerging technologies), as opposed to the Fraunhofer focus on more applied R&D and hence competitiveness within a single technology life cycle. Consequently, regional U.S. TBED strategies based on MII's or simply technology platform-focused clusters should have greater technology diversification and long-term growth potential.

Perhaps the most important policy point is that both economies are expanding the scope of their TBED strategies—just from opposite directions. U.S. strategies are expanding forward in the R&D cycle to augment the economy's traditional advantage in radical technology innovation.

[16] Brookings analysis of OECD data. See Parilla *et al* (2015).

Doing so emphasizes process technologies and better supply-chain integration in order to make continual product and process technology improvement over the entire technology life cycle the norm (Tassey, 2014a).

Meanwhile, the Germans, whose strengths are in the mid- and late-life cycle requirements for continuous improvement and process and quality control, and who have benefited from stable industry structures, are now emphasizing more radical innovation and diversity of innovation sources by promoting startups and organizing national efforts to transition to Industry 4.0.

In fact, the breadth and depth of startups in Germany have expanded to the point that Silicon Valley Bank, the dominant U.S. funder of domestic startups, has opened an office in Germany. One of its first clients was Lilium Aviation, which is developing electric flying taxis, requiring "a difficult combination of drone-like vertical take-off and forward jet propulsion".[17] Moreover, Germany has an accelerator program, German Accelerator Tech, that supports efforts by high-potential German tech startups to successfully enter the U.S. market.[18]

The important policy point is that German startups increasingly have a common emphasis on science-based innovation, in contrast to the traditional engineering-based focus. As *The Economist* points out, the portfolio of technologies targeted is also expanding to include heretofore largely ignored areas such as healthcare, e-commerce, and logistics services, as well as a continuing focus on advanced manufacturing. To support this expansion of targeted technologies, entrepreneurship programs are proliferating at German universities.

Finland

As globalization of the technology-based economy has expanded, the resulting growing number of economies (largely in Asia) that have acquired some degree of technological capability and combined it with lower wages has grown significantly. Most western economies have failed to respond adequately.

However, a few are making substantial investments in productivity-enhancing technologies and management techniques. Finland is one of the economies that have committed to a truly high-tech growth strategy. At 3.2 percent, their economy has one of the highest R&D intensities in the world and considerably above the EU average of 2.0 percent.[19] Prime Minister Matti Vanhanen stated that "Because we cannot compete with Asian companies with low wages, our only possibility has been to stay a few steps forward."[20]

What this means in policy terms is a focus on steady growth in innovation and productivity through a comprehensive TBED strategy. However, a small economy such as Finland is in effect

[17] "Taking Off: Entrepreneurship in Germany," *The Economist*, June 16th, 2018: 56-57.

[18] https://germanaccelerator.tech/.

[19] https://en.wikipedia.org/wiki/List_of_countries_by_research_and_development_spending. Data are for 2014.

[20] https://www.cnet.com/news/why-is-finland-europes-technology-leader-the-prime-minister-explains/.

the equivalent of a single regional economy in the United States. Thus, some significant degree of specialization is required and the TBED model must be applied rigorously and expertly. The largest companies have to operate on a global scale, requiring effective public-private growth strategies to achieve the scale and scope economies required for success (Kankanen et al, 2013).

Notably, the increasing scope of ICT and its effects on the variety and flexibility of communication and information applications is helping smaller economies rapidly upgrade their overall information infrastructure. In Finland's case, it ranks highest among OECD economies with respect to percent of enterprises using cloud computing services (OECD, 2015b).

Sweden

Sweden has a high-tech economy and one of the more systematic and well thought out national TBED strategies. Because of its small size, it faces the same imperative as Finland to achieve maximum efficiency from a focused technology portfolio.

The Swedish Government states that "innovation is vital to long-term productivity development, and thereby to growth and future prosperity". Further, the Government recognizes that the economic benefits from policies supporting innovation will be achieved only if a portfolio maximization strategy is used to identify and then support specific technologies targeted at identified economic and social goals.

This characterization of a modern technology-based economy has driven a comprehensive strategic planning and policy process in Sweden, which has resulted in set of targeted industries, markets, and social objectives. The implied hierarchy of goals making up the country's TBED policies is reflected in the *The Swedish Innovation Strategy* (2015):

> "An innovation can take the form of new products or technological solutions. It may also be new ways of planning and developing urban or rural areas and built environments. It can be combinations of goods, systems and services for the global telecommunications market or smart transport solutions. Innovation can also take the form of new ways of designing or organizing healthcare services for the elderly, new ways of submitting tax returns, new methods of involving customers or users in developing services or goods and new ways of taking advantage of and distributing art and artistic achievements. Innovation can also be new ways of using old, naturally occurring conditions, e.g., cooling energy-intensive data servers through localization in cold climates or new ways of using land, ecosystem services, raw materials from nature and biologically/ecologically based technologies and methods."

However, Sweden with a population of nine million people is equivalent to one of the many regional innovation hubs in the United States.[21] While the Swedish Government wants to promote diversification, it also recognizes the imperative to maintain sufficient scale and scope of its current investment targets in specific technologies. It therefore pursues active involvement in the broader EU economy.

In many ways this philosophy mirrors the evolution of innovation ecosystems in American state TBED policies. State economies benefit from the location of TBED investment, but the companies collocated in the innovation cluster must be able to access external sources of ideas, expertise, and eventually markets to be successful.

As is the case for U.S. innovation clusters, Sweden's TBED strategy emphasizes the selection and development of a unique set of assets to be used for the development and commercialization of unique technology platforms that can spew out applied technologies to be used by its domestic businesses to produce and offer goods and services in global markets.

In order to develop an efficient domestic innovation climate that can compete in targeted niche global markets, domestic businesses must maintain active relationships with customers and suppliers in global value chains and knowledge networks. The fact that exports represent half of Sweden's GDP seems traumatic due to the potential for inadequate access to foreign markets. In fact, Sweden's exports to Asian nations has declined in recent years, as these customers continue to invest in and become competitive in the same areas of technology.

Exports will obviously continue to be of crucial importance to Sweden's growth potential, so market segment targeting and subsequent appropriate investment is essential. In this regard, the concept of open innovation—access to a wider variety of sources of input into companies' innovation efforts—has become a major element of Swedish TBED policy design, as must be the case for U.S. regional economies.

The Swedish Innovation Strategy (2015) describes the open innovation imperative as

> "Open innovation is about businesses combining knowledge and ideas developed internally and externally. Open innovation implies that businesses actively involve external actors in their own innovation work. Phenomena such as "crowd sourcing", which is facilitated by new digital and social tools, enable involvement of expertise from a number of different sources, not always involving monetary rewards.
>
> Many businesses, from global business groups to smaller enterprises, are re-organizing their research and innovation activities towards open innovation. The level of investment in innovation can be retained, but the work is carried out by a small number of in-house personnel in collaboration with external actors in

[21] For example, the greater San Francisco area, which includes oldest U.S. innovation cluster, Silicon Valley, has population of approximately nine million people.

> universities, research institutes and other businesses, as well as with individual users and experts. The networks and relation of people, businesses and other organizations are therefore core factors in open innovation processes. The development of networks is facilitated by the mobility of people and efficient digital tools for social interaction."

The Swedish Innovation Strategy states that Sweden "will be a global leader in the utilization of the possibilities offered by digitalization." In effect, Sweden wants to be a leader in applying information and computer technologies (ICT) to promote the efficient and productive use of the internet and other digital services, as well as develop new e-services within both the private and public sectors. In addition, another goal is to ensure that digital information and digital tools will be utilized "in the best way possible within research and innovation" processes to create new products and services.

Such digitalization strategies are common among industrialized nations. What is perplexing is the almost total lack of attention in advanced economies' innovation strategies to the broader range of technical infrastructures that are essential to R&D productivity and advanced manufacturing. Such infrastructure exists, but it is extremely complex and is quality varies across technologies, as well as national economies. For example, any supply chain dependent on advanced materials must have access to computational modelling capability and highly accurate materials characteristics databases.[22]

In Sweden, there is still only a small proportion of small and medium-sized enterprises that collaborate through networks. Even more surprising, surveys from the Swedish Agency for Economic and Regional Growth indicate that the intensity of collaboration seems to be decreasing. Publicly-financed resources at universities and institutes for R&D, scale-up, and specialized equipment or test and demonstration facilities, are important resources in the innovation process conducted by small and medium-sized enterprises, who typically have inadequate resources for the entire TBED cycle.

Yet, *The Swedish Innovation Strategy* (2015) recognizes that "In the global knowledge economy, the importance of relationships among different actors in innovation processes is increasing". Thus, even though digital communication networks are improving the capacity for more formal interaction and knowledge exchange over long distances, the tacit character of early-phase technical knowledge development means that such knowledge does not transfer efficiently among researchers without direct personal contact. Thus, geographic proximity has become a major driver of innovation cluster formation.

Swedish policy development also recognizes the importance of a cluster's access to unique research facilities. This requirement is influencing the character of cluster formation all over the world. Examples in Europe are the European Spallation Source, MAX IV, and the SciLife Lab, along

[22] See Scott *et al*, 2018.

with numerous unique test and demonstration facilities for emerging technologies such as nanotechnology and biotechnology.

Switzerland

The economy of Switzerland ranks first in the world in the 2015 Global Innovation Index.[23] Switzerland is an example of a small economy that has invested intensively in a comprehensive TBED ecosystem supporting just a few targeted industries. The Swiss success underscores the fact that a regional focus in large economies, such as the United States, is appropriate in terms of scale and scope and, in fact, is actually desirable as doing so offers diversification for a large national economy.

OECD provides some interesting indicators of Switzerland's TBED strategy.[24] Starting with science, Switzerland has the highest number of Nobel Prizes per capita among European economies (25 Nobel Laureates with Swiss citizenship), which has been achieved in part through access to the nation's investment in world class research infrastructure, such as the European Organization for Nuclear Research (CERN). Another factor is the aggressive solicitation of top researchers from other countries. Switzerland is the country with the world highest proportion of foreign researchers. The result is that Swiss researchers produce 3.2 research papers per 1,000 inhabitants, ranking it tops in the world.

With respect to industry R&D and innovation, a large part of the business sector engages in R&D, although Switzerland has one of the smallest shares of BERD financed by government among the OECD countries. In fact, Switzerland traditionally refrains from granting R&D subsidies to business firms.

Yet, to turn science into economy-driving technologies, Switzerland, led by private-sector investment, still allocates 3% of its GDP to R&D, which ranks among the top tier of R&D intensities in the world. Importantly, unlike the United States, the Swiss federal government produces a strategic planning document every four years, the *ERI Message*, which provides an integrated framework for education, research and innovation policies that guide and support the national innovation ecosystem's support of its technology-based economy.

The Commission for Technology and Innovation (CTI), the main Swiss innovation promotion agency, supports market-oriented R&D projects, development of start-up companies and knowledge and technology transfer. As indicated above, the Swiss innovation system benefits

[23] https://www.globalinnovationindex.org/userfiles/file/reportpdf/gii-full-report-2015-v6.pdf. For an overview of the Swiss economy, see https://en.wikipedia.org/wiki/Economy_of_Switzerland. The Swiss have a number of world-class companies in a select set of industries: food processing (Nestlé), chemical for industrial and construction use (Sika AG), pharmaceutical (Novartis and Roche) and roof coating chemicals (LafargeHolcim is the largest construction materials group in the world).

[24] http://www.oecd.org/switzerland/sti-outlook-2012-switzerland.pdf.

from modern, high quality research infrastructures.

As an expansion of the technology investment priorities stated in the *ERI Message*, the State Secretariat for Research and Education in 2011 issued a roadmap for research infrastructures. Called the CH-Roadmap, it specifies planned investments in strategic areas and includes proposals for participation in international research infrastructures.

In support of the overall innovation ecosystem, the CTI focuses on encouraging higher education and public research institutes (PRI's) to collaborate with business. Most of its programs provide technical support rather than funding. Such support includes CTI Start-Up (mentoring and networking services for young entrepreneurs), CTI Invest (a venture capital platform), and Venturelab (entrepreneurship training).

Swiss multinationals are closely linked to global research and innovation hubs—the main way for a small economy (or regional hub in a large economy) to access economies of scope in major new areas of research. A federal strategy for the internationalization of education, research and innovation was adopted in 2010.

In addition to bilateral research agreements or cross-border cooperation (e.g. the Lead-Agency process with Germany, Austria and Luxembourg to co-ordinate funding decisions), the Swiss firms participate in EU programs (e.g. Research Framework Program FP, COST, EUREKA and the Lifelong Learning Program).

A major issue for the Swiss education system is the compartmentalization of its different education institutions, which affects internal mobility and access to higher education. The 2011 Law for the Support and Co-ordination of Universities aims to improve co-ordination between the Confederation and cantons, which are responsible for the quality of the higher education system.

United Kingdom

After decades of subpar performance by the U.K. economy, the Labor government came to power in 1997 and initiated a major effort to improve Britain's innovation policy. In addition to a national lag in R&D expenditures, the U.K. was an historic underperformer with respect to commercializing basic research. For decades the U.K. was known for producing a significant number of Nobel laureates and hence new science, but poor application efforts with respect to developing commercially viable technologies from that science.

In November 2000, the U.K. Government published *Productivity in the U.K.: the evidence and the Government's approach*. It concluded that "the U.K.'s productivity gap can be accounted for by its deficit in physical and human capital and its lower rate of innovation compared to other major economies."[25]

[25] HM Treasury, Productivity in the U.K.: the evidence and the Government's approach (2000), p. 17.

Richard Lambert, director-general of the Confederation of British Industry, issued a second report in 2003 that stated "Universities will have to get better at identifying their areas of competitive strength in research. Government will have to do more to support business-university collaboration. Business will have to learn how to exploit the innovative ideas that are being developed in the university sector".[26]

Stimulated by the Bayh-Dole Act, increases in U.K. public expenditure to fund science and knowledge transfers and hence to bridge the "valley of death" resulted in important progress. Significant increases in funding for university tech transfer offices were implemented in this decade (2001-2010). For example, Straw (2009) points out that Cambridge Enterprise Ltd., the university's commercialization office, experienced an increase in staff to 37, up from five people in 1999, and this was typical for major universities.

Of particular note, the number and size of regional innovation clusters and the value of companies within them have both increased (Straw, 2009). Given the importance of innovation clusters, it is noteworthy that the U.K. viewed the United States as encountering difficulty with attempts to create regional clusters around second-tier universities. While agreeing that the Massachusetts Institute of Technology and Stanford University stand out as the core of the two most successful clusters in the world, the view was also expressed that the U.K. may have nevertheless succeeded in outperforming the United States in terms of the commercialization initiative efficiency (success in creating technology development ventures). For example, when the University of Wisconsin at Madison and the University of Washington, Seattle, were ranked against U.K. universities generally thought to have inferior research capability, the U.K. schools actually performed better (Library House metric, 2008; Lord Sainsbury, 2007).

<u>China</u>

In analyzing foreign TBED policies, China, along with Germany, are the two most important case studies. However, they are important for very different reasons. As previously described, Germany, as a long-standing industrialized economy, has perfected its TBED policy structure in support of its target strategy of maximizing competitiveness in applied manufacturing technology. However, except for its intensive effort to be a leader in the emerging Industrial Internet of Things (IIOT), its innovation capacity does not seem to be above the average for industrialized economies.

China, on the other hand, while currently struggling to evolve from the "engineering innovation" phase of its evolutionary path to a mature industrialized economy, is also making huge investments in the TBED assets required to become a major player in "science-based" technology platforms, which produce the majority of radically new technologies and subsequent innovations. To this end, it is making significant strides in expanding and effectively

[26] Richard Lambert, Lambert Review of Business-University Collaboration: Final Report (2003), p. 2 (cited in Straw, 2009).

implementing the requisite TBED policies. Because of the scope and magnitude of the government's efforts in a large and growing economy, China is rapidly becoming a major player in global technology-based markets.

Much of the policy discussion surrounding China's economic growth policies centers on its mercantilist actions to artificially expand its trade surpluses through acquired technologies. The country has been relentlessly charged with directly stealing intellectual property from the U.S. and other advanced economies and indirectly forcing technology transfers through mandatory joint ventures with domestic firms.

The McKinsey Global Institute (MGI) in assessing China's future growth potential states that the Chinese economy will have to evolve from "an 'innovation sponge,' absorbing and adapting existing technology and knowledge from around the world, into a global innovation leader" (Dobbs *et al*, 2015).[27] This strategy was implemented (in other emerging Asian economies, as well) by focusing on labor force and capital expansion. Technology was largely acquired from external sources.

However, as wage rates have risen with a consequent decline in the efficacy of this strategy, the Chinese have seen clearly that their economy will have to invest in the full range of TBED assets that have appeared over the last two decades in varying degrees and in various forms in western economies. Asian economies, being younger, are therefore in the process of acquiring the required set of assets.

The MGI study argues that while China has become a strong innovator in areas such as consumer electronics and construction equipment, it has made little progress in advanced technologies such as biopharmaceuticals, automobile engines, and nanoelectronics. The study points out that this situation exists in spite of the fact that the country spends more than $200 billion on research (second only to the United States), turns out close to 30,000 PhDs in science and engineering each year, and leads the world in patent applications (more than 820,000 in 2013).

The study further argues that the Chinese have only reached competitiveness largely in "efficiency-driven" innovations; that is, they are competitive in relatively mature technologies where being competitive require (1) an emphasis on product improvements and efficient manufacturing and (2) a focus on customer- and efficiency-driven driven markets.

In contrast, becoming competitive in higher valued-added markets driven by radically new technologies will require China to a focus on new technology platform development derived from advances in science, which spawn whole new areas of product innovation opportunity (as indicated in the Technology Element Model depicted in Fig. 2).

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[27] The MGI study is a long and excellent assessment of the range of TBED policies and implementation experiences of the Chinese Government. Substantial use is therefore made of its content in this section.

With respect to the Chinese Economy's current state of evolution, the MGI study points out that it has an extensive ecosystem, which has provided an "unmatched environment for efficiency-driven innovation". The country has achieved the world's "largest and most highly concentrated supplier base, a massive manufacturing workforce, and a modern logistics infrastructure," which collectively give "Chinese manufacturers a lead in some important knowledge-based manufacturing categories, such as electrical equipment, construction equipment, and solar panels".

The Chinese manufacturing sector is progressing toward a higher technical level at a time when being competitive in a global manufacturing environment means moving toward a highly flexible manufacturing structure that includes increasing digitization not just within companies but in the broader technical infrastructure that supports advanced R&D. Moreover, global investment in such infrastructure is expanding across entire supply chains through the application of emerging IIOT infrastructure. The MGI study points to Guangdong province as the center of the Chinese competitive response, where manufacturers have set up joint platforms to share the benefits of R&D and operations among companies in the same clusters. The aggressive use of robots will significantly upgrade moderately skilled workers' productivity.

Still, as the MGI report points out, much of this effort emphasizes "accelerated learning," which is a global characteristic of "engineering-based" innovation (incremental advancement of existing technologies). Such efforts combined with purchasing by government-owned enterprises (market pull effect) achieve competitiveness in relatively mature technology-based industries such as communications equipment, wind power, and high-speed rail.

To elevate the Chinese economy to the top tier of technology-based economies, China's government will have to increase emphasis on TBED policies that focus on "science-driven" technology development. Here, the overall policy imperative is to become competitive in the early part of the technology life cycle by implementing higher degrees of cooperative research aimed at the development of new technology platforms derived directly from scientific advances (*Fig. 2*), which, in turn, can enable entirely new sets of engineering-driven market applications.

Moreover, long-term and broad success for a science-based TBED strategy also requires the creation and growth of startups to take on niche markets within the broader spectrum of markets emanating from new technology platforms that are the core growth engine for innovation clusters. Small firms also are critical because some of them will grow into large firms and give the domestic industry market presence in more applications of the core technology platforms.

In China, a new wave of entrepreneurs is emerging and starting to drive customer-focused innovation. Increasingly, Chinese youth aspire to launch businesses: in 2013, 12 percent of Peking University graduates said they had launched a company or were self-employed, compared with 4 percent in 2005. In a 2015 survey of college students on Renren, a social networking service, 56 percent said they would be willing to become entrepreneurs while in college.

Another source of entrepreneurial talent is returning students who have studied overseas. More and more students are returning to China, and in the Zhongguancun technology hub near

Beijing, an estimated 3,400 startups have been founded by some 8,000 returnees (Dobbs *et al*, 2015).

Access to early-round funding has improved dramatically. Funding by angel investors and early-stage venture funds grew by a factor of 14 between 2009 and 2014, rising to an annual rate of about $6 billion. Almost 70 percent of early-stage investment was in Internet and IT-related businesses. Alibaba, Baidu, and Tencent have invested more than $11 billion in approximately 100 ventures, looking for both investment returns and to fill the strategic needs of their businesses (Dobbs *et al*, 2015).

The rapid evolution of China's TBED ecosystem is evidenced dramatically by the country's rapid rise in the provision of venture capital. According to *Global Insights*, since 2012, Silicon Valley-based tech companies received a total of 12,000 venture capital financings, followed by New York-based companies with 5,000. With respect to funding, Silicon Valley companies brought in a total of $140B.

However, China (specifically, the emerging technology hubs in Beijing and Shanghai) are rapidly catching up to the leaders with respect to startups and venture financing. In fact, Beijing and Shanghai seem poised to be the tech hubs of the future. They lead among high-growth hubs for unicorns, mega-rounds, and large exits.

Most important, new company creation is accelerating. Half of the so-called "high growth" cities are located in Asia, where "high growth" is defined relatively high-dollar venture investments. Chinese cities are the dominant leaders.

Most cities with stable growth of startups and a higher concentration of later-stage rounds of financing are still in the United States, according to a survey conducted by CB Insights. However, about 80% of the Asian startups that hit the $1 billion milestone in capitalization between 2012 and 2017 (so-called "unicorns") are in China (mainly Shanghai which created 29 and Beijing creating 17). By comparison, Silicon Valley created 57 in the same period of time, but New York only created 13 (Bhardwa and Cheng, 2018).

Such investment is just one part of a broad and aggressive effort by the Chinese Government to push continual increases in both private and public R&D. However, the creation and use of TBED assets such as innovative small firms and their involvement in innovation clusters continues to lag. Further, intellectual property rights management is a continuing problem.

Overall, the Chinese TBED strategy is a major force in the ongoing process of "global convergence" beginning with Japanese ascendency to the status of a "technology-based economy" in the 1980s.[28] This process is ongoing today, largely in the form of Asian economies'

[28] The process of convergence is a phenomenon going back centuries in which emerging economies catch up with (growth faster than) the global leaders by acquiring skills and assets from the leaders and combining these assets with lower-cost labor. The process is abetted by the fact that the leaders tend to rely on accumulated stocks of capital, which experience diminishing returns to a greater extent than in emerging economies where

acquisition of existing technologies, which are not only embedded in capital but "engineered" to further enhance newly attained comparative advantages.

The process of convergence is abetted by the ability to "engineer" existing technology (as pointed out by Dobbs *et al* (2015), which accelerates convergence and even leadership in markets based on moderately mature technologies. Still, this strategy only works for a while. As success breeds higher productivity and hence higher labor incomes, these newer economies must convert to a broader and integrated TBED strategy to induce more domestic innovation in newer, emerging technologies.

In this regard, China has been accused of using the lure of a huge domestic market to force foreign firms to transfer technology to Chinese companies as the price for access to this lucrative market. While true, the emphasis on this tactic distracts policymakers elsewhere from the much broader set of TBED strategies summarized here, which the Chinese Government continues to expand and fine-tune. In fact, China enters the contest for leadership in the next era of manufacturing with strong advantages, including its extensive manufacturing ecosystem, large labor force, and modern infrastructure.

In summary, Chinese manufacturers can adopt advanced technology and build on China's advantages within an increasingly digital ecosystem that will link all participants in the manufacturing ecosystem, refine hybrid automation models, and facilitate open design and manufacturing platforms (Industry 4.0). As is the case for Germany discussed earlier, aggressive policy actions can yield for China the flexibility, variety, and mass customization that global markets are increasingly demanding (Dobbs *et al*, 2015).

The implications of the above characterization of the emerging innovation capacity of what will soon be the world's largest economy are summarized by

> "China can become a platform for accelerated innovation, not just for Chinese companies, but also for foreign multinationals that want to take advantage of Chinese cost and speed to produce innovations for China, emerging markets, and the world. Moreover, the Chinese model for rapid, low-cost, and nimble innovation can be adapted for use around the world. The overall effect could be accelerated innovation globally, challenges to market leaders from new innovators, and new, lower-cost products and services that fill unmet needs of emerging-market consumers and keep up with the shifting demands of consumers

newly acquired capital can be combined with lower-cost capital and labor. Thus, the argument by economists has been that all economies should eventually converge in terms of per capital income (https://en.wikipedia.org/wiki/Convergence_(economics)).

in advanced economies." (Dobbs *et al*, p. 12).

There is another critical element of Chinese TBED policy structure that is essential to long-term growth in an increasingly competitive global economy. As in other major industrialized economies, manufacturing in China is evolving from a capital-intensive sector, which in the past has led to industry structures dominated by a relatively few large firms, which, by acquiring substantial IP and attaining some combination of economies of scale and network externalities that favors giant corporations with massive scale, have been able to dominate both domestic and global markets.

Today, however, market drivers such as mass customization, open innovation, and digital infrastructure are drastically lowering minimum efficient scale for competitive operation, especially within regional clusters where tacit knowledge and interactive relationships can flourish. This has led to an explosion of small firms, leveraged by regional technology-based infrastructure.

In summary, this "democratization" of manufacturing is effected by a "maker" movement in which individuals and startups can translate good ideas using online design tools to develop new products using a network of engineers and designers within the cluster and then contract for their development and manufacture with production facilities using advanced techniques such as 3D printing. China's manufacturing ecosystem provides an ideal environment for an explosion of innovation.

For example, Between 2003 and 2014, China accounted for 35 percent of global growth in wind power capacity. To effect needed technology transfer, the government imposed localization rules under the Wind Power Concession Project—requiring 50 percent local content starting in 2003 and 70 percent starting in 2006, As a result, foreign manufacturers and suppliers established plants or joint ventures in China, and in so doing, created regional clusters where domestic players could access global talent and knowledge networks.

In summary, this forced technology transfer policy had significant effects on the evolution of knowledge in the wind-power industry, where technology transfer, local-content regulations, and investments in domestic capacity deepened Chinese engineering capabilities. The 2003 Wind Power Concession Project helped China's wind-power industry advance quickly along the learning curve (Dobbs *et al,* 2015).

However, just as the design and implementation of TBED policies across the 50 U.S. states has been uneven, Chinese companies have not performed particularly well in other industries that have also been the targets of regional TBED strategies, such as in the automotive sector where Chinese companies have less than 10 percent of global revenue. In this sector, the innovative capacity of Chinese automakers has been limited by a weak supply chain, resulting in limited opportunities to benefit from collaboration with suppliers on new products (Dobbs *et al*, 2015).

In emerging technologies, the Chinese Government has become increasingly aggressive. For example, to promote the development of electric vehicles, the Government has provided substantial R&D subsidies, as have other industrialized nations. However, the Chinese have also implemented demand-pull policies in the form of significant purchase subsidies to increase consumer demand, but also designed to pull specific product technology attributes such as longer life batteries. The government has set a target market of three million units per year by 2025. The scale of the discount to buyers is set at Yuan 34,000 (roughly $5,300) for cars with range of 250-300 km, Yuan 45,000 for 300-400km and Yuan 50,000 for cars 400 km and above.[29]

Perhaps most important for long-run success, the Chinese understand the importance of a complete TBED strategy, as is found in large, mature innovation clusters such as Silicon Valley. For example, the MGI report points out that electric vehicles require the integration of three evolving technologies: batteries, electric motors, and control systems.

The policy implication is that being successful in complex emerging technologies, such as electric vehicles, requires a comprehensive multiple supply-chain strategy. To this end, not only has the Chinese government invested $6 billion across the several technology categories, it has also driven the formation of consortia of "car manufacturers, suppliers, and infrastructure players" (Dobbs *et al*, 2016).

In addition, like Europe, the Chinese government is investing in critical infrastructure to accelerate market penetration by electric vehicles through subsidization of electric charging stations. Such acceleration of market penetration will feed back into the evolution of the innovation cluster by stimulating more investment in scale-up and production capabilities. These investments are being driven by a 15-year roadmap prepared by the Society of Automotive Engineers of China for the Ministry of Industry and Information Technology (Fusheng, 2016).

These TBED policy elements emphasize the critical importance of the innovation cluster model for China's transition to a science-based innovation economy. In this regard, China has three major innovation cluster cities—Beijing, Shanghai, and Shenzhen—and a group of smaller but rapidly growing innovation clusters in other cities.

And, the Chinese Government is applying similar comprehensive TBED strategies in other important emerging technologies. It has initiated major research programs in autonomous vehicles, cyber systems, and artificial intelligence. China's long-term strategy calls for "partially-autonomous" cars to account for 50 percent of sales by 2020. "Highly-automated" cars (not quite fully autonomous) will take 15 percent of sales in 2025. By 2030, fully autonomous vehicles are expected to account for 10 percent of sales, which in the huge Chinese market means sales of 4 million complete robocars annually (Dunne, 2016).

As (Dobbs *et al*, 2015) describe in some detail, Beijing stands out as center of technology innovation. 26 of 112 national universities are located in the Beijing area. Foreign high-tech companies have research centers in the Beijing area, including IBM and Microsoft. Leading Chinese tech companies, including Lenovo, Xiaomi, and Baidu, are headquartered in the

[29] Source of subsidy estimates: Citi (https://www.platts.com/latest-news/metals/london/citi-bullish-chinas-new-subsidy-program-for-long-26974717). Referenced in Dobbs *et al* (2015).

Zhongguancun district of northeastern Beijing.

The second of the three major Chinese innovation clusters is Shanghai, which is becoming the hub for life sciences, and includes contract research organizations that serve both Chinese and global companies with clinical trials and other outsourced services.

The third major innovation cluster, Shenzhen, was designated as a special economic zone in the 1990s and has become the center of tech and Internet startups, including Tencent and Huawei. More patents have been awarded to Shenzhen companies than to companies in Beijing and Shanghai combined. Proximity to electronics manufacturing operations in Guangdong Province has made Shenzhen a center of tech hardware innovation.

At the core of any economy's TBED strategy is a robust technical infrastructure that leverages the productivity of all technology foci (Tassey, 2014). Information infrastructure is obviously a critical component. As part of its determination to move beyond engineering-based innovation (characteristic of "middle income" economies), China has made huge investments in information technology. Tanzi (2018) points out that "90 percent of U.S. advanced technology imports from China are information and communications goods that include computer central processing units, peripherals and telephone switching components". Census data show that this IT trade with China resulted in a deficit of $151 billion in 2017.[30]

As China's regional TBED ecosystems continue to evolve, more foreign high-tech companies will locate within these innovation clusters. The implication for U.S. TBED policies is that individual efforts by state governments will not evolve sufficiently to match the coordinated and high priority support from national governments in other economies, such as China. The combined national and regional government efforts will help innovation clusters first reach minimum critical mass and then grow to an optimal size at which rates of innovation and economic growth will be maximized.

However, as mentioned briefly above, this characterization of China's TBED strategy ignores the other side of Chinese growth strategy, which is an aggressive mercantilist approach to obtaining foreign technology and subverting open competition from foreign companies trying to compete in China's large and lucrative domestic market.

As described by Ed Gerwin in a Progressive Policy Institute (PPI) report, "the linchpin of China's future-oriented mercantilism is an extensive array of plans, policies, rules, and practices to enable the transfer and assimilation of foreign technology and intellectual property for China's benefit.

To achieve these goals, China is employing many unfair or illegal measures, including using foreign ownership restrictions and licensing approvals to compel American and other nations' companies who wish to do business in China to transfer their technology. Further, the Chinese Government directs and funds a highly coordinated effort by Chinese state-owned and private

[30] See https://www.census.gov/foreign-trade/statistics/product/atp/2017/12/atpctry/atpg04.html.

firms to acquire foreign tech firms. China's conduct poses a threat to the United States where IP-intensive industries alone support more than 45 million jobs and represent 39 percent of U.S. GDP (Gerwin, 2018).[31]

Equally important for the future, after several decades of currency manipulation to create unfair comparative advantage in support of its engineering-based innovation strategy, the new focus of Chinese state industrial policy is on higher value-added industries based on science-based innovation strategies, as described above. Executing this strategy demands quick and massive absorption of IP to enable the targeted transition and to provide Chinese firms with the experience and capability to become science-based innovators.

As Nager (2016) points out, keeping the Chinese currency (RMB) artificially low is less important than it once was. China is instead ramping up aggressive technology acquisition mechanisms as a precursor to the goal of achieving sufficiency in internal innovation-based growth strategies. Thus, he argues that China continues to be the culprit in persistent U.S. trade deficits, just through a different path.

Moreover, China has not become guiltless with respect to currency manipulation. The traditional approach to manipulating one's currency is to directly intervene in currency markets. China has done this for years by buying U.S. debt, which creates a demand for dollars and thereby raises the value of the dollar relative to the yen.

Today, China still buys our debt but has not used this tool in an aggressive manner to directly manipulate the bilateral exchange rate. This "backing off" from direct currency manipulation, however, does not mean China has forsaken this technique altogether. By subsidizing exports and thereby lowering their prices, the Chinese Government is effectively depreciating its currency with respect to the competitive positions of competing economies for these export markets.

Another argument is that the loss of U.S. jobs in the heavily traded manufacturing sector is due more to productivity increases, which lowers labor content per unit of output, than to currency manipulation. Such an assertion is important for addressing the central issue of this paper: the relationship between TBED policies and the resulting increases in productivity, and the long-term growth in jobs and also in workers' incomes.

The fact is, while increasing productivity does lower labor content per unit of output, it also makes exports more competitive in global markets, thereby raising output and global market shares. This the best of all possible scenarios because the increase in sales stimulated by higher productivity (greater performance and/or lower cost) raises output, which requires more labor

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[31] Also see United States Trade Representative, "2017 Report to Congress on China's WTO Compliance," pp. 2-12.

is required even with lower unit labor content. And, because companies pay for productivity, workers receive higher incomes, as well. If this were not the case, how could Germany with one of the highest labor compensation rates in the world manage to achieve persistent trade surpluses (Tassey, 2018a).

The bottom line for TBED policy is that developing and using technology as the tool for achieving long-term high rates of growth in productivity is the only way to raise workers' real incomes over time. Government growth policies must support the public-good components of each competitive asset category.

South Korea

Beginning in the mid-1980s, the Korean Government ramped up programs to encourage high-technology industries such as semiconductors, where engineering-driven innovation could be applied to improve on science-based innovation elsewhere, in particular the United States. As has been the case with China, the Korean TBED policy focus began to shift in the 1990s to more knowledge-intensive industries in which science was increasingly directly drawn upon to create new technologies. This shift, in turn, required increasing domestic investment in a broader array of policy instruments, which drove regional innovation cluster development (Enterprise Society, 2012).

A National R&D Program was initiated to coordinate and fund a range of policy instruments to raise the economy's R&D intensity and, in particular, to increase industrial firms' R&D spending. The latter was achieved by generous R&D tax incentives. By 2007, 80% of Korea's R&D expenditure was occurring within the private sector. South Korea's national R&D intensity is now 4.23 percent, compared to 2.74 for the United States.[32]

Most important, like China, South Korea has recognized the need to elevate its existing "industrial complexes," in which only modest co-location synergies were being achieved. In particular, while production agglomeration was realized in support of engineering-based innovation strategies, there was not sufficient R&D capability to achieve the desired "innovation complexes" (Ministry of Knowledge Economy, 2010).

As a result, South Korea's Government has focused intensely on developing a set of institutions and industry structures to effect the desired shift to a science-driven technology development and innovation strategy. Recognizing the growing complexity of emerging technologies and therefore the imperative to co-locate large and small firms within a regional supporting ecosystem, the Korean Government developed and implemented four major policy thrusts (Enterprise Society, 2012):

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[32] Country data are for 2015. Source: NSF, *Science and Engineering Indicators*, 2018 (https://www.nsf.gov/statistics/2018/nsb20181/assets/1038/tables/tt04-05.pdf).

(1) Fostering of region-specific industrial clusters. Supported by national and local government. Regional innovation councils were set up to oversee the development of the clusters.

(2) Creation of environments conducive to the fostering of entrepreneurship and innovation. Industry structure incentives, such as support for startups and small firms generally, access to financing, business support services, targeted education and training, and university-driven R&D.

(3) Enhancement of a collective learning processes within innovation networks. Includes strategies such as the removal of legal and regulatory obstacles to inter-firm cooperation. Also included were incentives for collaborative research between industry and universities, plus access to professional services and the fostering of social networks.

(4) Regional social capital. Support from community and other non-government organizations, who provided networking forums such as conferences, workshops and seminars both within South Korea and with neighboring economies, such as Japan, Singapore and China, to promote cross-border collaboration for education, research and company partnering.

A major institutional element of this overall strategy is a set of Government Research Institutes (GRIs) to support the development of new platform technologies, which can spawn new industries. They are therefore comparable to the U.S. Manufacturing Innovation Institutes (MII's).

Korea has a long history of promoting co-location synergies. Until the last decade, however, most clustering was just production agglomeration; i.e., such clustering did not include sufficient R&D capability.

Recognizing that this situation was not a sufficient infrastructure for the industry-university-institute collaboration on R&D required to achieved science-based innovation status, a major effort was initiated to elevate the economy's TBED infrastructure and overall innovation strategy. This effort, ongoing for the past two decades, consists of the implementation of an Industrial Complex Cluster Program (ICCP) at seven model complexes in multiple economic regions of the Korean economy.

The overall purpose of ICCP is to upgrade each region to true global innovation clusters centered on designated technologies and associated markets. These efforts have focused on integrating complementary research functions for each technological focus under an industry-university-government institute framework. The long-term goal is to upgrade the productivity of R&D capabilities through enhanced inter-cluster exchange and collaboration (i.e., achieve risk pooling, economies of scope in early-phase technology research.

In terms of actual organizational strategy, this policy thrust has been implemented through the establishment of "mini clusters". Mini Clusters refer to relatively small alliances of a range of "companies, universities, research institutes, supporting organizations, and local governments, grouped by the types of strategic business or technological characteristics. For example, the Changwon cluster, which has adopted machinery as its strategic business, has organized and operated mini clusters that specialize in machine tools, molds, transportation equipment, mechatronics, and metal materials" (Ministry of Knowledge Economy, 2010).

So far, about 60 mini clusters have been initiated by the Korean Government. The Government directly manages the structures, objectives and working methods of all 60 mini clusters, which leads to a uniformity of structure and overall management.[33]

7. TBED Policy Instruments and Overall Policy Structure

An OECD (2015a) report emphasizes that most of the key technologies in use today, such as the Internet and genomics, "have their roots in public research, illustrating how essential public investments are". Thus, as underscored in OECD (2017b), the design, implementation, and management of national innovation strategies are critical to economic success.

Such a statement can be labeled as obvious, but implementing it effectively and consistently is not trivial. The process of developing a national strategy requires involvement of all stakeholders across the entire technology life cycle. As discussed here and in Tassey (2018a), individual policy instruments are typically applied at specific phases of a technology's development and commercialization. This reality, coupled with the fact that the actors involved at each phase are to varying degrees different, imposes real management and coordination requirements on the overall ecosystem.

To be efficient, however, TBED policy instruments must be designed for maximum impact in overcoming specific patterns of underinvestment. For example, R&D is supported by both government funding and targeted government tax incentives (Tassey, 1996). The two policy tools target different market failures. So, policy makers must choose wisely.

In implementing a comprehensive TBED strategy, the total amount of resources committed is also a critical indicator, as it indicates the level of commitment to technology as the key driver of long-term growth in output (GDP) and income. In this regard, the OECD (2015a) report points out that the U.S. economy ranks just below the median in terms of spending by government and higher education institutions on R&D in 2007 as a percentage of resulting GDP in 2013.[34]

Although the U.S. economy was the clear technological leader for several decades after World War Ii, the needed evolution of its innovation policy compared to other nations has lagged. For

[33] In contrast, two basic forms of clusters exist in Germany. One is "bottom-up" clusters, which are industry driven and largely managed by the private sector. The other, "top-down" clusters, are initiated and controlled by government. Source: TCI (http://www.tci-network.org/news/81Cl).

[34] The implication is an assumed six-year lag between the R&D spending and the impact on GDP.

example, this country was the first to implement an R&D tax credit. However, other economies, seeing the value of this incentive, imitated the U.S. initiative and subsequently expanded its size.

In the late 1980s, the U.S. credit was the most generous among OECD members. But, the Information and Technology Foundation (ITIF) has calculated that the United States has steadily fallen in the relative generosity of this policy tool for stimulating private-sector R&D. By 2004, the U.S. credit had fallen to 17th. By 2014, the United States ranked 19th among OECD countries and 27th among all countries measured, and its ranking has continued to slip. In 2016, the U.S. ranked a low 25th among just the OECD nations and 26th for small and medium-sized enterprises. (Kennedy and Atkinson, 2017).

More broadly, and hence even more serious, is the fact that the U.S. Federal Government has no comprehensive set of TBED policies that are organized into an ecosystem to serve as a model for individual states, as well as to provide state governments with direct financial and technical support. More generally, the U.S. has no substantive and comprehensive innovation policy function at the federal level.

As OECD has stated, "The development and implementation of innovation policies also require strong capabilities within the public sector, including in building trust in government action and ensuring the support of stakeholders for policy actions, assuring co-ordination between individual economic agents, as well as fostering greater experimentation in the economy" (OCED, 2017).

As a general principle, establishing a goal-based national strategy for innovation is one thing; its implementation is often another matter. Most industrialized nations seem to realize that the development of new technology platforms should be at the top of the national economic investment agenda and have invested in building the institutions and capabilities needed for discovery and invention, as described in this paper.

While progress is being made toward this holistic (ecosystem) objective, investments in most countries have not yet reached the size and scope to attain targeted TBED efficency. China, for example, is not a top global competitor in major science and innovation driven industries. For example, it has less than a 1 percent share of global revenue in branded pharmaceuticals, 3 percent in biotech, and 3 percent in semiconductor design. In these markets, Chinese firms still tend to focus on lower value-added products, such as generic pharmaceuticals. Its struggles reflect both how long it takes to build science-based innovation capacity despite its large investments in R&D (Dobbs *et al*, 2015).

The policy message is that the development of TBED policies must recognize that each economy operates in a complex, dynamic and uncertain environment, where government policy initiatives will initially, at least, be inadequate. Thus, a commitment to monitoring and evaluation of policies, and then learning from experience and adjusting policies over time, is the only way to ensure that government action is efficient and will reach its objectives.

This imperative for a competent and well-resourced national policy capability creates considerable concern for the U.S. TBED policy structure. While individual states are ramping up both the scale and scope of specific policy instruments, they are doing so without anywhere near the scale and scope of support needed from the Federal Government. In contrast, leading technology-based economies such as Germany and China have a much more committed central government role.

A additional point can be made that may appear to be a contradiction to the repeated emphasis on regional specialization and sufficient investment to achieve both scale and scope economies at the regional level. That is, companies within a TBED cluster will likely benefit not only from involvement in other regions, but also from participation in other countries' regional hubs.

In this regard, as Dobbs *et al* (2015) point out, this could mean locating more R&D activity in emerging technology-driven economies such as China, where, for example, Microsoft has funded 3,000 scientists and engineers in its Asia-Pacific Research and Development Group in Beijing. Similarly, Chinese companies can strengthen innovation capabilities by adding R&D facilities in other markets or using overseas R&D joint ventures. Lenovo executives credit having dual headquarters in Beijing and North Carolina with helping the company achieve global leadership in PC sales.

Most important, policy learning rests on a well-developed institutional framework, strong capabilities for evaluation and monitoring progress, applying identified good practices, and an efficient government bureaucracy. Incorporating policy monitoring and evaluation will support evidence-based decision making and accountability and enable policy learning over time, as can formal experimentation with policies at a small scale Tassey (2014b). Better measurement of innovation outcomes and impacts is essential in this context.

The major policy message is that the lack of a substantive U.S. Federal Government strategy implemented through an institutionalized TBED policy infrastructure is placing too great a burden on individual state programs. Learning, scale and scope effects, and simply increased investment need national government support, shown by the discussions of other economies' TBED strategies. In today's increasingly competitive technology-driven global economy, governments compete against each other as much as do private companies.

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