The Economic Rationales and Impacts of Technology-Based Economic Development Policies

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Beginning with the Second Industrial Revolution, the US economy grew to become the world's leader by doing the one thing that drives long-term increases in incomes: investing in productivity growth. This productivity impact of this investment was realized through the creation of new technologies that were then embodied in new types of equipment creating new products at lower cost. The country also invested in educating its workers to use these technologies efficiently. And finally, substantial public investment was undertaken, which created a world-class infrastructure that leveraged the efficiency of commerce.

Today, ever expanding globalization demands even more investment in productivity growth to outperform a growing number of global competitors. This investment must be targeted at an increasingly technology-driven economy, derived from the above four categories of investment:

technology, hardware and software, skilled workers, and modern economic and technical infrastructures. Extremely important is that the nature of this investment requires effective cooperation between government and industry. Yet, support for such investment has been uneven and poorly conceived. In the absence of adequate domestic incentives, U.S. companies have reduced their investment in the domestic economy and allocated resources elsewhere in the world (Tassey, 2017a).

The failure to face up to globalization, especially once its scope and hence impacts began to accelerate in the 1980s, has caused large numbers of US workers, especially the lower middle class, to lose ground. As more and more countries upgraded the skills of their workers and invested in productivity enhancing technologies, a relentless global labor arbitrage ensued. The resulting "offshoring" of investment and the simultaneous increase in the amount and diversity of imports forced remaining domestic workers to accept stagnant or even declining real incomes to keep their jobs.

Inadequate investment in the above four investment categories has resulted in weak productivity growth. Since the Great Recession, labor productivity has grown at one-half the average annual rate for the first 25 years after World War II. The unfortunate consequence has been wage and income stagnation, and hence little growth in the standard of living. More telling is the fact that real incomes were declining well before the recession. Bureau of Census data show that real median household income—the major metric for assessing growth in the standard of living—is unchanged in this century (2000-2016).[1]

We once had much better economic growth strategies. Government funding of the early phases of new technology development spawned virtually every major technology driving the U.S. economy in the post-World War II era. U.S. labor out-skilled the rest of the world and U.S. companies with little foreign competition were willing to invest over the longer periods of time necessary to bring new technologies to market, which raised productivity and hence workers' incomes.

In the face of inadequate policy responses by the Federal Government, state governments are increasingly attempting to take up the slack. This paper assesses these efforts within the context of a technology-based economic development (TBED) model.

1. Introduction

TBED is economic growth driven by technology and a number of key supporting assets. For societies that wish to create not only jobs but raise the incomes of workers, a technology-oriented economic growth strategy is the only approach.

Economic studies like Jones and Williams (1998, 2000) have estimated the return on research and development to be four times the return on investment in physical capital, implying that TBED strategies should be substantially increased. The difference between worker incomes in technology-driven industries and other sectors of an economy is dramatic. For the U.S. economy,

[1] Bureau of Census Historical Income Tables: Households (https://www.census.gov/data/tables/time-series/demo/income-poverty/historical-income-households.html).

the Bureau of Labor Statistics (BLS) data show that high-tech workers earn 70 percent more than the average for all industrial workers (Jones, 2014). The substantial wage differential is due to the fact that technology is the long-term driver of productivity growth and companies pay for productivity.

Katz and Muro (2014) summarize the economic impacts from promoting "advanced industries":

> "Advanced industries are manufacturers, energy providers and service firms that are fueled by research and driven by science, technology, engineering and mathematics (STEM). They punch way above their economic weight, making up only 9 percent of our country's workforce but generating nearly 18 percent of our GDP, 58 percent of our exports, 81 percent of our patents and 90 percent of our private research and development. What's more, according to Moody's data, advanced-industry workers earn an average of $90,000 per year compared to $47,000 for our economy as a whole."

This significant difference in economic impact should clearly focus economic growth strategies on technology as the core investment policy. However, only 13 percent of the U.S. workforce is classified as being in the "science, technology, engineering, or math (STEM)" category, which clearly indicates that the current U.S. economic growth strategy is inadequately focused on the technology-productivity-growth nexus (Tassey, 2018a).

The most common metric for assessing a nation's commitment to competing on the basis of productivity-enhancing technology is its spending on R&D. In this regard, although experiencing a steadily declining share of global R&D, the US economy still spends about 30 percent of the total spent. While substantial, it means that for every dollar spent on R&D within the US economy, two dollars are being spent elsewhere in the world. Moreover, NSF data show that federal R&D spending—critical because a major portion is spent on breakthrough research that drives new industries and future high-paying jobs—has declined as a share of GDP by 41 percent over the past 40 years.[2]

Moreover, as this paper discusses in detail, R&D spending is only a summary indicator of an economy's commitment to compete on the basis of technology. A large number of more specific investment strategies and a variety of institutional support mechanisms are needed as part of a regional TBED strategy:

- Public-private R&D funding and coordinated spending and conduct strategies,
- R&D infrastructure support (advanced materials data bases, efficiency of research methods, process control methods, etc.),
- Provision of skilled labor in all STEM categories,
- Public assistance for starting high-tech firms and using technology transfer mechanisms to acquire available technology,

[2] https://www.aaas.org/page/historical-rd-data.

- Scale-up for production support,
- Market entry and penetration assistance

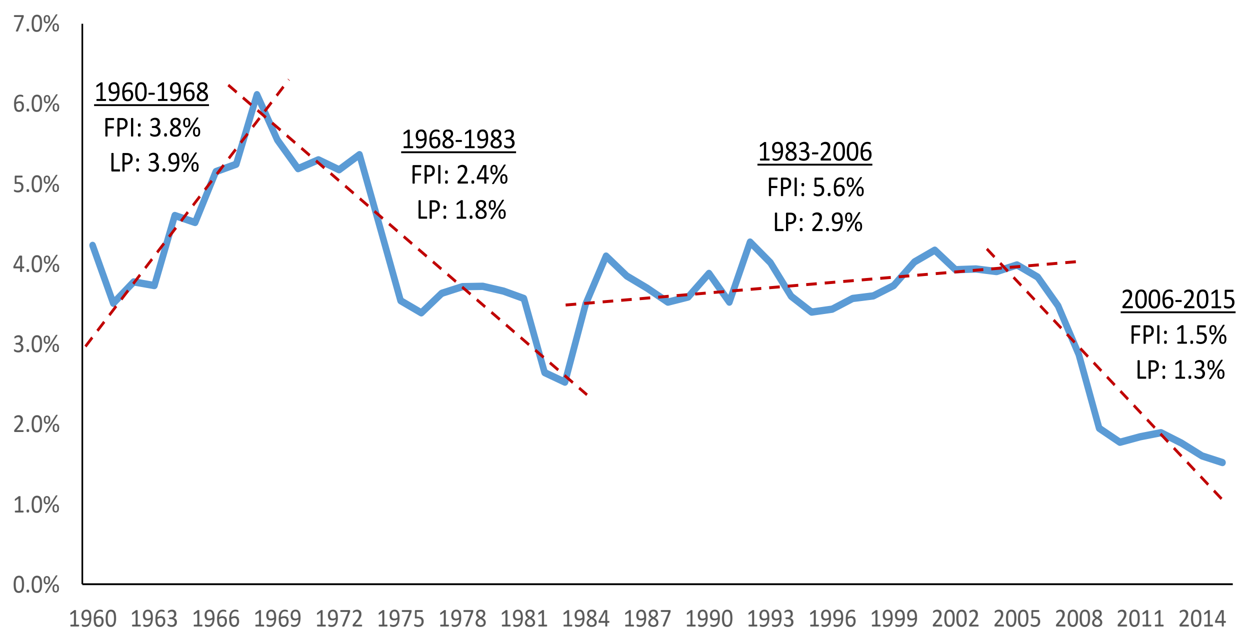
A recent trend retarding the needed transition to a comprehensive economic growth policy is the fact that national policy discussions in the post-recession period have fixated on the slowness of the recovery—with little attention to the longer-term structural weaknesses that have progressively constrained the growth rate of the domestic economy.

In summary, the above indicators show that the rate of U.S. economic growth has been slowing for decades, including greatly reduced growth in real incomes. The culprit is globalization, which has created a growing number of technology-based competitors around the world who are increasingly capable of taking shares of high valued-added markets at the expense of U.S. domestic industries.

The Economics of Decline

As indicated above, instead of increasing productivity-enhancing investments in technology and innovation, national policy makers have relied almost exclusively on a monetary policy-driven strategy of low interest rates and the demand-stimulation dimension of fiscal policy. In the 2000's, cheap credit led to more excessive borrowing in a desperate attempt to compensate for the lack of investment in the economic assets that drive real income growth. The result was real estate and

Fig. 1 **Average Annual Real GDP Growth for 10-Year Periods Compared with Private Investment and Productivity Growth (FPI = fixed private investment; LP = labor productivity)**



Source: Bureau of Economic Analysis for GDP data; Bureau for Labor Statistics for Productivity data

stock market speculation, and eventually the worst recession since the Great Depression.

The long-term growth problem resulting from inadequate investment is shown dramatically in *Fig. 1*. In the 1960s, fixed private investment (FPI), largely hardware and software—the means by which new technologies are introduced into the into an economy and thereby have their productivity impacts—was quite high and, as a result, labor productivity grew at a healthy annual rate of 3.9 percent.

But, in the following 15-year period (1969-1984), global economic upheavals discouraged domestic investment and the rate of productivity growth declined dramatically. A modest policy response occurred in the subsequent two decades (1984-2004), as years of R&D targeting information technology (IT) paid off in the form of increased productivity growth. IT investment was particularly strong in the late 1990s. Unfortunately, there was no significant follow-on in terms of investment in additional technologies and, with globalization increasing, U.S. investment and productivity growth collapsed. Obviously, there is a serious economic growth problem.

The Growth Policy Challenge

Instead of emphasizing investment to accelerate productivity growth, the Federal Government responded to the recession with even more aggressive monetary policies that resulted in the Federal Reserve balance sheet growing from $800 billion in 2008 to $4.5 trillion by 2014. The critical point is that these policies are business cycle stabilization tools, which are useful only in addressing short-term disruptions along a long-term economic growth track. The prolonged cheap credit found its way into financial markets, which mostly benefited wealthy individuals, while providing no incentives to companies to make long-term investments in research and innovation.

So, the message is clear: invest in the right technologies, hardware and software, labor skills, and advanced infrastructure to raise productivity or fail to compete. Competing through productivity growth is the only way to increase market shares and both the number of jobs and workers' incomes over time. Unfortunately, our policy makers at the national level have not gotten the message. Neither political party has a productivity-oriented growth strategy, so the effective growth policy has been to hide from global competition (Tassey, 2018a).

However, increasing exports relative to imports is not a trivial challenge, as evidenced by the fact that the US hasn't had a trade surplus in manufacturing since 1975, and even the high-tech portion is now running a deficit. The bottom line is that in a modern, technology-driven global economy, governments compete against each other as much as do domestic industries. And, they compete by providing incentives to invest in economic assets that drive productivity growth and thereby increase competitiveness. Currently very little attention is being given to the imperative to invest in four categories of competitive economic assets identified in this section.[3]

2. *Economic Assets for Technology-Based Economic Development*

With the average worker's real income basically stagnant for several decades, state governments are increasingly attempting to compensate by developing and implementing TBED policies aimed at raising the productivity and overall competitiveness of their regional economies. Collectively, these policies embody a wide range of specific institutional and financial mechanisms, which states

[3] On exception is the U.S. Government Accountability Office, which issued a 2018 report stating that "the extent to which the United States is able to focus R&D investment in key technology areas will be a key factor in U.S. competitiveness in the global economy." See https://www.gao.gov/products/GAO-18-396SP.

typically modify to accommodate the unique set of technology-based components making up their local economies and the strategic directions that are required for competitive success.

However, establishing, improving, and effectively using TBED policies is a challenging task. Different policies affect different phases of a technology's development and its commercial applications. The public-good content of TBED economic activity varies significantly both in nature and amount over a technology's life cycle. This fact means that TBED policies must be constructed for a range of private-sector underinvestment behaviors that change in level and character at each phase of the technology's life cycle. Thus, the application of each policy instrument must be adjusted over time in response to industry's needs as the evolution of the targeted technology proceeds.

Individual TBED policy instruments typically target one of the following four major economic asset categories (Tassey, 2017a):

- ***Technology:*** The core driver of long-term productivity growth.
- ***"Fixed" capital:*** Hardware and software that embody most new technology and, thereby, enable its productive use.
- ***Human capital:*** Skilled labor capable of designing and using the new hardware and software and associated techniques.
- ***Technical and institutional infrastructure:*** Public-private infrastructure to leverage the development and use of modern complex technology systems.

Modern technologies are increasingly complex systems. The extent of this complexity has eliminated or at least reduced the existence of the single dominant high-tech firm. Thus, companies such as IBM, Xerox, Kodak, and AT&T that once dominated their respective industries, in that they developed both system components and the final product or service system itself, have been replaced by supply chains of R&D-intensive firms that create, produce, and market innovative high-tech components that are eventually integrated into the final product or service system. In many industries, companies who once accounted for most of the R&D in its supply chain now specialize in system integration, purchasing virtually all components from upstream suppliers who are becoming increasingly R&D intensive.

While this evolutionary change complicates regional government targeting of companies whose location within their economies would be desirable, it also offers the opportunity to expand the set of resident industries, which increases potential value added within the regional economy and also diversifies the risk of individual firms leaving the local cluster.

The critical economic message for regional governments is that local infrastructure supporting technology development and commercialization greatly affects the productivity of the entire technology-based economic process from technology development through production scale-up and initial commercialization to market development. The latter stage is where the majority of economic benefits are delivered, but the efficiency of the preceding two stages determines the amount, quality, and speed of delivery of these benefits. This fact underscores the importance of timely provision of technical and financial infrastructure support over a technology's entire life cycle.

With respect to the scope of economic activity targeted, the four technology-based economic asset categories cited above must be utilized to create four areas of capabilities or resources within state TBED programs:[4]

(1) **Emerging Technology Research Capacity.** Initiatives that expand and strengthen the capacity to conduct proof-of-concept research by universities, federal labs, and the private sector in a cooperative setting through institutional mechanisms such as university-industry partnerships, innovation "hubs", and "manufacturing innovation institutes" that create the new technology platforms that allow subsequent innovation to occur. The local development of technology platforms is incredibly important, as the efficiency of innovation efforts drawing upon such platforms is significantly increased by the co-location of the universities and private companies involved in a platform's development and all companies attempting to develop commercial applications based on it.

(2) **Technology Development and Commercialization Capability.** Initiatives that (1) promote the application of new technology platforms to create applied technologies and products with high commercial potential, (2) encourage and facilitate small-firm formation, and (3) facilitate development of their commercialization strategies by supporting pilot-scale production and scalability testing.

(3) **Government/Industry Infrastructures** that

    a. Encourage entrepreneurship by increasing the capacity of entrepreneurs to successfully start and grow companies by improving the effectiveness of entrepreneurial training and opportunities to participate in emerging industries through orientation of business school curricula, accelerators/incubators, and provision of technical infrastructure (standards) to facilitate entry into high-tech supply chains.

    b. Provide access to scientific and engineering databases, high-speed Internet, and other local communication and computing infrastructures.

    c. Increase investment in education through focused training facilities and curricula facilitated by co-location of universities and community colleges that (1) encourage more students to enter STEM fields by providing internship programs and technical training for workers in existing companies and (2) train entrepreneurs in the skills needed to manage young, high-tech companies.

(4) **Access to Risk Capital.** Increasing the availability of capital to support startup and emerging companies through angel investor tax credits, direct funding of technology-based companies through programs such as SBIR, and help companies access venture capital sources.

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[4] See "What is a TBED?" by The State Science & Technology Institute (SSTI), for an alternative taxonomy (https://ssti.org/TBED).

In the following sections, the policy mechanisms for creating and effectively implementing these TBED capabilities will be described in terms of (1) their economic rationales (i.e., the market failures that rationalize various policy responses), (2) the specific elements of each policy mechanism and how they are intended to remediate targeted underinvestment gaps, and (3) projected economic impacts predicted by existing studies and policy assessments.

These investments are increasingly competing with growing investment across the global economy, including in emerging economies with lower labor costs. In recent decades, the productivity/cost advantages attained in other economies have significantly restrained the effectiveness of the U.S. economy's modest and inconsistent national response. The bottom-line economic impact has been an offshoring of jobs and significant constraints on the wages of domestic workers. Perhaps more threatening for the future is the growing investment by other economies in "science-based innovation", which produces next generation and radically new technologies—something the US economy once dominated.[5]

To be effective, US policies must be developed in the context of substantial differences in the nature of technology-based growth. Economies of scale drove the Industrial Revolution of the 18th and early 19th centuries. In this period, product diversity was limited and thus competition centered around reducing unit cost. That is, reducing cost for firms producing fairly homogeneous products was the dominant economic growth strategy. Today, however, high-tech products and services are much more diversified and evolve more rapidly, which creates pressure on product and service development strategies to be both more productive and yet less costly.

3. The Rise of Regional Technology-Based Growth

The realization is spreading across state governments that technology-based growth is essential for long-term job and income growth. As the State Science & Technology Institute (SSTI) puts it

> "Competing in a global economy, regions must have an economic base composed of firms that constantly innovate and maximize the use of technology in the workplace. Technology-based economic development, or TBED, is the approach used to help create a climate where this economic base can thrive."[6]

However, as global competition has expanded and attempted responses have proliferated, differential impacts across state economies are occurring due in large part to significant variations the scope and depth of growth policy responses by individual state and local governments. Many state governments have expanded their programs and overall efforts to upgrade their economies, as part of a broader expansion of state roles.

As this paper will demonstrate, these efforts are having substantial impact on state-level economic growth. However, a wide range of efficiency levels exist with respect to the design of individual policy tools and their integration into an overall TBED strategy, as will be discussed in the following sections.

[5] See Tassey (2018b) for an assessment of foreign government TBED strategies and policies.

[6] From SSTI, "What is a TBED". See https://ssti.org/TBED.

The scope and level of investment in such programs varies across states, but almost all states seem to be increasing such investment to varying degrees. This fact raises the need for effective policy frameworks that allow government officials to choose the right policy mechanisms for each stage of the technology-based growth process. Further, technologies evolve in cycles, which means state governments must be able to adjust resources across policy mechanisms for each phase of a targeted technology's life cycle.[7]

This complexity presents both opportunities and challenges for state economic development. The opportunity is the potential to use investments in a comprehensive set of technology-based investment mechanisms supported by a technical infrastructure that leverages private investment, not just in single industries but across an entire emerging supply chain of related industries, thereby creating large numbers of high-paying jobs.

However, the broad set of needed TBED elements, as described in the following sections, must not only be efficient in terms of creating and delivering needed technology-based inputs and services, but it must be directed by an effective planning infrastructure that can (1) enable selection of specific technological targets upon which to focus scarce resources, (2) facilitate adaption to the increasingly rapid pace of technological change, and (3) provide a business infrastructure to enable effective commercialization strategies.

As Microsoft's CEO, Satya Nadella, puts it, "there's no such thing as a perpetual-motion machine. At some point, the concept or the idea that made you successful is going to run out of gas. So, you need new capability to go after new concepts. The only thing that's going to enable you to keep building new capabilities and trying out new concepts long before they are conventional wisdom is culture."[8] In other words, states need a dynamic policy framework that guide decision making over the entire technology life cycle and also embraces the long investment lead times necessary of timely commercialization of new technologies.

In spite of these challenges, TBED activity is expanding in most states. Atkinson and Wu (2017) point out that "policy discussions about America's innovation-driven, high-tech economy too often spotlight just a few iconic places, such as the Route 128 tech corridor around Boston, Massachusetts; Research Triangle Park between Raleigh, Durham, and Chapel Hill, North Carolina; Austin, Texas; Seattle, Washington; and, of course, California's always white-hot Silicon Valley." The fact is that most states now have a TBED policy infrastructure in place and are seeking to expand its impact on state economic growth.

Atkinson and Wu further argue that policy analysts and many government officials have a "too myopic a view of how innovation is distributed across the country, and it is increasingly out of step with reality, because many other metropolitan areas and regions—from Denver to Salt Lake City to Minneapolis and St. Paul—are becoming innovative hot spots, too."

Scott Pattison, executive director and chief executive officer of the National Governors Association (NGA), observes that states are more important now. He posits that the main question states are asking is: "How can we prepare our workforce and our economy—our citizens and our

[7] See Tassey (2007, 2013) for discussions of the economics of technology life cycles.

[8] "Microsoft's Next Act", interview in *McKinsey Quarterly*, April 2018.

society—for unprecedented change?" Further, he argues that state governments "are recognizing that they must address the skills gap together, regardless of political affiliation." Finally, an important policy issue is "how federal R&D policies affect states, and how state governments' roles in shaping local and regional innovation ecosystems will affect national R&D competitiveness and economic growth" (NAS, 2018, p. 1).

To help state policymakers select, construct and implement individual TBED policies and to effectively manage their combined use over entire technology life cycles, the remainder of this paper reviews the generic TBED policy instruments and provides examples of each from various state programs to indicate alternative forms of each instrument and the range of economic impacts to be expected. These instruments are then aggregated into a policy structure and some empirical evidence of their collective impact is presented.

Such an integrated policy framework has been largely ignored at the Federal Government level, leaving it to state governments to reinvent and improve upon individual policy tools and then try to manage them collectively as an integrated policy system. However, it is essential for successful regional economic performance to have a guiding conceptual framework of the entire "innovation ecosystem," as the high-tech economy is a complex entity and must be managed accordingly.

4. A Conceptual Model of the Elements of TBED Programs

For decades IBM, like other large research and development-intensive companies, conducted virtually all research associated with the development of new computer technology platforms within its corporate boundaries. Today, in order to be competitive in the emerging field of nanoelectronics, IBM is a major investor and participant in New York's Center of Excellence in Nanoelectronics and Nanotechnology located (CENN) at Albany State University, where the company is partnering with other electronics companies (like Intel, Micron, AMD, Texas Instruments and Freescale Semiconductor, Inc.), as well as with smaller companies who are often suppliers to IBM) and, importantly, with several universities. The New York state government is a major financial supporter and the federal government is directly involved in the research. This investment would be unlikely to happen in anything like the same scope and quantity without this kind of extensive public-private cooperation.[9]

Geographic "clustering" of high-tech economic assets is spreading primarily because of the existence of significant "co-location" synergies associated with the development, diffusion, and commercial use of modern technology systems.[10] For emerging technologies, the scope of the overall research required to develop the initial "technology platform" is largely beyond the research capabilities of even large firms. This is because such technologies are increasingly complex combinations of scientific disciplines that must eventually operate as an efficiently functioning product or service "system". The research assets required to produce each system component are

[9] See Wesler (2008) and https://www.sunypoly.edu/research/centers-programs/index.html.

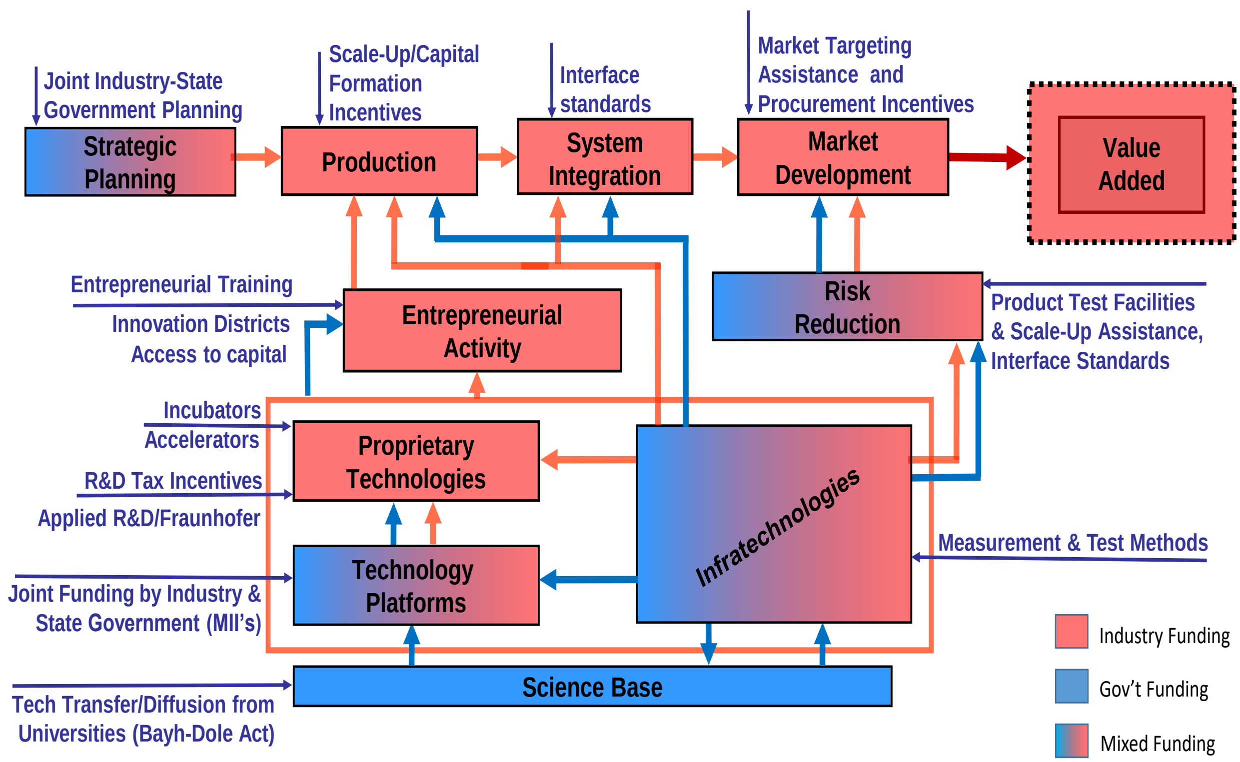
[10] Chesbrough (2003) was the first to describe the process of "co-location" synergies in which firms generate new technological concepts, develop them into products and services, and then pursue commercialization through both utilization of both internal and external sources of ideas, technical information and specific production and marketing knowledge.

distinctly different and therefore require unique sets of skilled labor, research facilities, and research infrastructure. Plus, before commercialization can occur, these components must be integrated into an efficiently functioning system.

The message is that effective TBED policy requires a conceptual framework that identifies and characterizes each "technology element" in terms of its role, economic impact, and both type and degree of public-good content. The last of these characterizations is critical for designing and managing TBED policies.

Fig. 2 is a conceptual model of these technology elements and their relationships, depicting the general order in which these elements are developed and hence the flow and progression of technical information through the R&D and commercialization stages of a technology's life cycle, and the degree of public-good content in each stage of the TBED sequence. Thus, this Technology Element Model (TEM) indicates the development and commercialization sequence (arrows) of the typical modern industrial technology. It also characterizes the various elements in terms of their public-good content (red for private good, blue for public good) and hence the appropriate role for government in support of each element.

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



Based on Tassey (2007, 2010, 2014)

To begin, all modern technologies originate from advances in science, produced largely by universities (bottom of Fig. 2). In the past, such knowledge slowly and inefficiently diffused into industry where technological applications were developed. Hence, the gestation period for science-based innovation was very long.

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 based on their scientific advances and very early technology development (i.e., improve the efficiency of the transfer of scientific knowledge).

The process of transforming science into technology and eventually innovations 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. The linear progression of economic activity across the top of the diagram was the way economists characterized the economic growth process before technology became the critical input. Not addressing the issues associated with the vertical progression of successively more applied technology will result in inefficient progress along the top of *Fig.2*.

More specifically, science is 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 that are typically beyond the set of target markets of even large R&D-intensive companies, demands a public-private cooperative approach to efficiently conduct such research.

The broad scope of the required research, the early point in the R&D cycle (which means considerable technical and market risk), and the uncertainty as to ownership of the resulting IP all contribute to underinvestment by individual firms. However, crossing of the "valley of death" to achieve a technology platform is essential for efficient innovation, so policymakers must have viable strategies for efficiently executing this transition (Tassey, 2007, 2014).

From a policy perspective, the resulting "proof of concept" is extremely important in facilitating the much larger later-phase R&D investments (which is largely undertaken with private funding). Because of the collective (industry-wide) use of technology platforms, direct participation of industry in the research process facilitates early and more efficient 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 resources by individual companies, such as the research consortium that developed the technology platform, universities, government laboratories, and other sources of technical knowledge. 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, which diffuses more readily through person-to-person contact (Tassey, 2007).

Thus, both funding and conduct of this early-phase research are done in an interactive physically close environment. The public-good content also means that government funding is essential. For example, Mazzucato (2013) points out that the early phases of development of the multiple technologies that make the iPhone a 'smart' phone were funded by government (GPS, Internet, touch screen display, and the SIRI voice activated system). This is also true of many high tech firms like Compaq and Intel, which received early stage financing not from private venture capital, but also from government support efforts such as the Small Business Innovation Research (SBIR) Program.

Today, the technical risks are higher due to greater technological complexity and the consequent requirement for multidisciplinary research approaches. In contrast to the Industrial Revolution when economies of scale dominated, economies of scope now provide significant barriers to individual company investment and therefore provide the rationalization for collaborative funding and the conduct of the early phases of R&D (specifically targeting the "technology platform" phase of R&D in Fig. 2).

With respect to financing this early-phase research, at which point the development pathways and timing are uncertain, traditional venture capital firms are less willing to assume the technical and market risks, especially given the long time to commercialization at this early phase of the R&D cycle. A funding gap therefore persists with respect to pursuing science-based innovations, especially those with new and unique advances, as risk-adjusted expected rates of return will be too low.

The critical policy point is that the roles industry and government play and the needed policy support changes over a technology's life cycle. This fact means the state 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.

As a general premise, policies must fill private-sector investment gaps as they exist at any point in time at the various phases of TBED identified in Fig. 2. However, because both the private and public dimensions of TBED activity evolve with the changing nature of technologies, the breadth and depth of foreign competition, and the opportunity set determined by other regions' technology specializations, such policies must be managed in a dynamic manner by an informed public-private infrastructure that has both the correct policy model and the data to drive it. The ultimate efficiency of TBED policy will be determined by the amount of investment in and efficient management of the four broad asset categories (technology, fixed investment, skilled labor, and technical infrastructure) stated in Section 2 above.

Across state TBED programs, application of the TEM leads to a number of policy targets:

(1) Provide an efficient R&D infrastructure that facilitates combining research assets from regional public and private sources top create new technology platforms that can spawn a range of new applied product and process technologies;
(2) Improve the efficiency of industry R&D by facilitating the conversion of science and subsequent technology platforms into applied technologies and products with high market potential through cooperative research centers, entrepreneurs, start-ups, and established companies that collectively develop commercialization strategies based on regional technology development and then access local pilot-scale production and scalability testing facilities.
(3) Promote a dynamic and innovative industry structure by enriching the skills and ability of entrepreneurs, increasing their capacity to successfully grow companies, and improving the environment for entrepreneurial development, using venture development organizations, mentorship programs, accelerators, incubators, and innovation orchards.

(4) Provide "digital-age" infrastructure, emphasizing wireless broadband that connects not only people but also machines through sensors, databases, and other information technologies to boost productivity and hence competitiveness.

(5) Increase access to capital to support startup and emerging companies is critical. Regions can address needs for capital through angel investor tax credits, investing in technology companies, using public funds to leverage private investment funds, and help companies access capital sources.

(6) Facilitate scale-up to efficient production levels.

For these TBED policy goals to become a reality, they must be converted into a set of "investment strategies" with specific targeted outcomes in order to secure necessary funding. Such a set is listed in *Table 1*.

Table 1 **Implementation Targets of a Regional TBED Policy**

(1) Increase *aggregate investment in R&D* and thereby leverage the local economy's R&D intensity

(2) Establish research mechanisms that focus on developing new *technology platforms,* which are critical for high rates of innovation and the creation of new industries

(3) Encourage more the development of integrated local supply chains that deliver more diversified (and hence sustainable) regional growth

(4) Foster *technology infrastructures* that increase R&D and production efficiency over the technology life cycle and enable *market entry* by SMEs

(5) Update and expand the *educational infrastructure* to create deep and diversified *labor pools* that are required to attract new private-sector investment

(6) Increase the *speed and breadth of the diffusion* of new technologies to accelerate rates of local economic growth

(7) Enable *rapid scale-up* to achieve commercially efficient volumes of production

(8) Improve regional economic policy management techniques through planning & evaluation

The design and management of these policy implementation targets must recognize that each set of suppliers (different tiers in the target high-tech supply chain) requires special technology, capital, labor and infrastructure assets that are applied at different phases of TBED life cycle and that have different degrees and types of public-good content and hence requirements for government roles/policy responses.

5. TBED Policy Instruments—R&D Support

The following discussion characterizes the individual policy mechanisms that function within the above economic framework and which are available to state TBED planners. It then indicates how these mechanisms interact with each other over a technology's development and commercialization life cycle. The second part of this analysis—interactions among individual TBED policy instruments constitute the dynamic dimension of a regional innovation ecosystem and presents the most challenging element of modern TBED strategies.

The implementation framework for the set of TBED policies in *Fig. 2* is the regional "innovation cluster". Efficient design and operation of such "ecosystems" require not only private investment, but also a robust largely public technological infrastructure that supports high-tech supply chains and overall productivity through application of a range of policy tools.

Although an increasingly dominant element of the state-level policy response is to emphasize technology-based growth strategies, until the last couple of decades, only a few centers of regional technology-based growth existed. The oldest and largest is Silicon Valley, which grew out of the Stanford Research Park in the 1950s and '60s to become one of the largest and most diversified technology-based clusters in the world.[11] Today, this concentration of high-tech firms has spread to the entire San Francisco area, which has the largest concentration of high-tech companies in the United States, employing 387,000 high-tech workers. Not surprisingly, Silicon Valley also has the highest concentration of high-tech workers of any metropolitan area, with 286 out of every 1,000 private-sector workers engaged in this high-tech cluster. Silicon Valley workers have the highest average high-tech salary in the United States of $144,800.[12]

In response, regional programs such as the Maryland Innovation Initiative and MassDevelopment Manufacturing Innovation Grants, as well as seed funding from family, friends, or angel investors provide additional sources of venture capital. However, such early-phase private risk capital is increasingly hard to obtain due to (1) the complexity of modern technologies and (2) the consequent longer gestation periods before reaching the commercial prototype phase of the R&D cycle (10 years for biopharmaceutical technologies, for example). Thus, when investors apply a risk-adjusted discount rate to potential early-phase venture investments, less private venture funding is occurring.

If start-ups are able reach the prototype stage, traditional venture capital may be obtained. Such funding can then support these young companies through the final stages of product development and manufacturing scale up. The policy problem is to get young firms to that point (Singer and Bonvillian, 2017).

This demanding challenge can be addressed by a number of public and private-public policy tools that are increasingly important in today's TBED ecosystem, as described below.

<u>Universities</u>

In terms of technology-based economic growth, universities have historically been functionally separated from high-tech industries due to their traditional dominant role conducting scientific research. "Science" has traditionally had little direct process connection to eventual efforts to

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[11] See https://en.wikipedia.org/wiki/Silicon_Valley#Stanford_Industrial_Park.

[12] "Cybercities 2008: An Overview of the High-Technology Industry in the Nation's Top 60 Cities".

develop industrial innovations other than to provide the scientific base for technology development. This separation results from the fact that scientific knowledge has been simple enough to be diffused by indirect means (most university research was simply published when completed with little subsequent direct interactions with those who drew upon it for the purpose of technology development).

However, in recent decades, the growing complexity of technology has complicated the transition from scientific research to early technology development. The more iterative role of new science is reflected in the process of creating equally more complex technology platforms—hence, the metaphor crossing the "valley of death". This more complex transition led university research to integrate forward into the early phases of technology development, with university researchers increasingly participating in proof-of-concept *technology* research.

Effectively managing this more iterative transition between science and the early technology proof-of-concept phase has significant potential for improved regional TBED strategies, as the U.S. has 39 of the top universities in the Leiden Impact Rankings. The implication is that the skills and knowledge embodied in these universities' faculties should be useful for raising the productivity of increasingly science-driven technology development.

This forward integration of university expertise led to a growing ability of universities to attain intellectual property (IP) rights. Universities, however, initially did not see themselves as owners of technology IP. Policymakers therefore concluded that, as early actors in technology development, incentives were needed to stimulate the transfer of such technical knowledge forward in the R&D cycle. The need to promote such early-phase technology transfer led to the passage of the Bayh-Dole Act of 1980.

This legislation was an early and generally perceived effective policy mechanism for promoting transfer of intellectual property (IP) created by Federal Government sponsored research from universities to industry. The Act requires universities to file for patents when appropriate from such research, as a first step in created IP that could then be licensed to industry.

Functionally, the motivation for universities to own the intellectual property (IP) from federally funded research created a huge opportunity for expanding local innovation activity derived from a regional cluster's university IP. The policy target is to increase the number of technological innovations developed by licenses issued by a university to local small firms, many of which were spinoffs from the university stimulated by IP ownership.

However, even though patents codify knowledge and thereby facilitate transfer, the complexity of modern technical knowledge means that the absorption of the new knowledge and its subsequent utilization in developing new technology platforms typically require technical assistance from the creator. By locating innovative firms, especially small ones, near the source of the knowledge (the university), the initial absorption and subsequent utilization in early-phase technology research is enhanced. Such "co-location synergies" are increasingly important for R&D efficiency.

Providing an incentive to universities to promote commercialization efforts for university IP appears to have had the desired impact targeted by Bayh-Dole. Hausman (2012), analyzed Census data relevant to university-based local economies after the passage of the Bayh-Dole Act and found that both long-term employment and worker incomes rose in industries more closely related to local university innovative strengths.

However, to further enhance the rate of innovation within clusters, a broad integrative policy mechanism needed to promote synergistic interaction among the major small-firm policy instruments. For example, Link *et al* (2018) find that ”firms that received SBIR funding and partnered with a university were, compared with similar firms that did not partner with a university, less likely to commercialize their technology, less likely to retain employees who were hired to help with the funded project, and less likely to realize employment growth beyond what would have been predicted in the absence of the award” (p. 32).

Link *et al* focus on the biopharmaceutical industry. However, this industry presents some unique conditions such as the existence of multiple overlapping intellectual property claims by universities doing federally funded research for which the Bayh-Dole Act applies. This situation has led to considerable disruption of the perceived university-industry ecosystem concept. For example, patent infringement law suits have arisen between universities and industry over alleged industry use of what universities consider to be IP developed within their federally-funded research programs.

In summary, universities' traditional role of conducting basic science is not an issue. Scientific knowledge is a pure public good and should therefore be freely available and distributed. However, because modern technologies are becoming more complex and because global competition is shortening windows of opportunity, the scope of university research has justifiably expanded forward into the "valley of death"—the transition between science and the early phases of technology development (i.e., proof of concept). That is, utilizing universities' unique research skills is increasingly essential at this transition point in the technology life cycle. But doing so requires more efficient management of this phase of the R&D cycle, specifically managing IP and achieving co-location synergies in the proof-of-concept transition phase of R&D.

However, although not widely recognized, the evolving R&D infrastructures are at least partially solving the "Bayh-Doyle problem". As described below, new infrastructures such innovation hubs/clusters and "innovation districts" are integrating university research into the broader R&D effort with IP issues specified early in the R&D cycle by the collective management of the cluster, or at least among engaged members of the cluster. Such "institutional innovation management" mechanisms are essential to efficiently cross the valley of death and provide the new technology platforms that drive the applied R&D and the subsequent innovations that create profits and worker income growth.

<u>Expansion of Collaborative R&D as Regional Growth Efficiency Mechanism</u>

A cross-cutting feature of evolving state TBED strategies is the emergence of and dependence on various forms of collaborative research. For several decades, collaboration has been used as a standalone mechanism for improving the efficiency of early-phase (proof-of-concept) research. Sematech was an early example of such "research consortia".

However, Parilla *et al* (2015) emphasize the advantages of "collective knowledge," spillovers from clusters of firms, and pools of skilled labor. These "high-tech assets" are anchored by supportive institutions such as universities, research institutes, community colleges, and industry consortia.

The resulting ecosystems are becoming the core of regional economic growth strategies. As will be demonstrated in Section 10, the collective economic impact is substantial.

As part of the evolution of innovation clusters, collaboration has been increasingly extended to include adjacent tiers in an industry's supply chain. The economic significance of this trend is to significantly expand the potential economic growth impact from the regional TBED strategy. Further, the collaboration mechanism is also being expanded beyond just research to the supporting infrastructure to increase the availability of skilled labor and venture capital for small companies, including startups, that contribute to both technology development and subsequent production of innovative technologies.

An example is the Printed Electronics Research Collaborative (PERC) at the University of Massachusetts Lowell.[13] Similar to 3-D printing, which uses additive manufacturing processes to build up plastic or metal materials, printed electronics "prints" circuits in a variety of forms—from rigid and planar to flexible, conformable, and embedded. This technology has a wide range of product applications, including such disparate targets as wearable medical devices, printed batteries, and smart packaging for food that can detect spoilage. Primarily through fast prototyping, this technology can potentially shrink the time from design to manufacture from months to days.

It is important to note that the consortium's purpose, broadly stated, is to create an additive electronics supply chain within the Massachusetts economy, which includes the encouragement of startups, and the facilitation of workforce training. Individual corporate members, such as the Raytheon-UMass Lowell Research Institute, have employees co-located in the same building with faculty and students, thereby creating research synergies. Fourteen companies have joined PERC so far, representing many needed components of the target supply chain.

A second example is the Institute for Advanced Composites Manufacturing Innovation (IACMI).[14] IACMI is one of the 14 Manufacturing innovation Institutes (MII's), which are established by combined federal and industry/state funding. This regional consortium stretches across six partner states—Colorado, Indiana, Iowa, Kentucky, Michigan, and Tennessee.[15]

IACMI represents about $250 million in combined investment from Manufacturing USA/DOE and from state and industry partners. The institute functions largely by creating research partnerships that drive innovation in the manufacture of advanced carbon fiber composites in support of three application areas: vehicles, wind turbine blades, and compressed gas storage.

Seventy percent of IACMI's work is focused on vehicles, and specifically on developing materials

[13] Based on presentation by Craig Armiento of the Printed Electronics Research Collaborative (PERC) at the University of Massachusetts Lowell summarized in NAS (2018).

[14] Based on presentation by John Hopkins of the Institute for Advanced Composites Manufacturing Innovation (IACMI) summarized in NAS (2018).

[15] The MII's are authorized by The Revitalize American Manufacturing and Innovation Act, passed in 2014. However, the federal funding comes from mission federal R&D agencies through the Manufacturing USA Program managed by NIST. For example, because IACMI is a Department of Energy (DOE)-funded center, its focus is on reducing energy consumption.

and manufacturing methods that can lower the cost of carbon fiber components, so that multi-market penetration is possible. Significantly, the Institute has three application areas: vehicles, wind turbine blades, and compressed gas storage. This increases the complexity of the consortium, which is evidenced by the fact that IACMI has participation by partners in six states. As with any geographically dispersed and multi-tier supply chain entity, managing the financial and business interactions across these partners is complicated.

John Hopkins of IACMI points out that "the six states represent about 70 percent of the automobile manufacturing production in the United States," which offers potentially huge economic impact. For example, IACMI has a facility in the Detroit area to help meet the need for automotive implementation of carbon fiber, another in Indiana at Purdue University, and smaller operations at other core partner settings. The breadth of the potential economic impact is seen in the fact that the Institute has partners in several tiers of this advanced materials-driven supply chain, including smaller and medium-sized companies in earlier tiers, who are critical for efficient and large-scale implementation of automotive applications (NAS, 2018).

From a policy targeting perspective, it is interesting to note that the stated long-term goal is for the MII to provide the linkage between core innovation assets and the companies who need large-scale demonstration and other assistance in moving it into full-scale implementation—encompassing deployment in addition to the more common pure research focus.

6. TBED Policy Instruments—Ecosystems

As discussed in previous sections, modern technologies have become more scientifically driven, more complex, exhibit large economies of scope, and longer gestation periods before commercialization. These trends create the need for an array of institutional mechanisms to support the process of de-risking technologies and addressing expanded development timelines before the commercial prototype phase is reached—the point at which private venture capital is willing to fund commercialization.

In these earlier, pre-venture capital phases of R&D, significant efficiencies are realized from the various aspects of "clustering" of technology-based economic assets, including (1) shared research facilities, (2) skilled labor pools, (3) industry infrastructure (start-up and small firm assistance), and (4) technical infrastructure (access to scientific and engineering databases). Some of the more important aspects of these mechanisms are discussed in this section.

Innovation Clusters

As previously discussed, the problem of technological complexity, which affects all phases of the R&D cycle, scale-up for production, and actual market penetration, is being mitigated by the evolution of TBED research infrastructures such as "innovation hubs" or "manufacturing innovation institutes (MII's)," which are "clusters" of private and public entities, including universities and compamnies, who cooperatively conduct early-phase technology research relevant for several tiers in a high-tech supply chain.

A major benefit of clustering of TBED assets is the fact that 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. These networks, which are becoming the backbone of regional economies, together constitute the key driver of industrial competitiveness.

Muro and Katz (2010) define an innovation cluster as

> "geographic concentrations of interconnected businesses, suppliers, service providers, coordinating intermediaries, and associated institutions like universities or community colleges in a particular field (e.g., information technology in Seattle, aircraft in Wichita, and advanced materials in Northeast Ohio). By facilitating such dynamics as labor market pooling, supplier specialization, and knowledge spillovers, industry clusters benefit all sorts of firms and regions by enhancing the local and innovation potential, encouraging entrepreneurship, and ultimately promoting growth in productivity, wages, and jobs."

The earliest innovation clusters, such as Silicon Valley, evolved in an unstructured fashion and hence slowly over time. Today, however, shortening global technology life cycles and the consequent need for more rapid domestic productivity growth demand a much more structured and rapidly implemented set of policy instruments.

Michael Porter (1998) first drew attention to the important role of clusters in American industry. Since then, the regional cluster growth model has steadily evolved. Slowly, its institutional role as an engine for high-tech, high-productivity, high-income growth has become recognized.[16]

As stated by Muro and Katz (2010), "it is now broadly affirmed that strong clusters foster innovation through dense knowledge flows and spillovers; strengthen entrepreneurship by boosting new enterprise formation and start-up survival; enhance productivity, income-levels, and employment growth in industries; and positively influence regional economic performance." Baily and Montalbano (2018) add "Clusters (or innovation districts) have been found to increase the innovation levels, efficiency, and productivity with which participating companies can compete, nationally and globally.[17]

The importance of clusters for rates of innovation is evidenced by their ability to attract venture capital. Venture capital (VC) investments are increasingly concentrated in innovation clusters, where the synergistic effects of high-tech firm co-location and innovation infrastructure raise the probability of high rates of return.

As summarized by Singer and Bonvillian (2017), nearly half of VC investments in recent years have occurred in Silicon Valley. Three other regions with concentrations of high-tech infrastructure—the New York metro area, Los Angeles/Orange County, and New England—accounted for another third of national VC investment. All other regions received modest amounts at best. As a result, for start-ups outside these major areas, access to venture funding has been severely limited. These trends have been fairly consistent since the 1960s.

The more limited precursor of clusters, the research consortium, and the cluster model itself have

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[16] It is important to note that the rest of the industrialized world understands this trend, as well. See Tassey (2018b).

[17] Baily and Montalbano provide a number of insightful examples of existing clusters.

evolved by expanding and better integrating a set of economic assets and institutions and creating management infrastructures that deal with a range of public, public-private, and private economic assets. For example, with respect to R&D conducted cooperatively within a cluster, IP ownership is worked out in advance for the various phase of the technology's development, so all parties know who has access to what parts of the overall target technology platform and subsequent commercialization efforts.

In this context, the concept of a Manufacturing Innovation Institute (MII) offers accelerated evolution of a cluster infrastructure. The public portion funding for an MII derives from both the state where it is located and a federal R&D agency with a need for advances in the target technology. The Federal Government's contribution to each of the 14 MII created so far is managed by the Manufacturing USA Program at the National Institute of Standards and Technology (NIST).

An MII provides a localized ecosystem consisting of a university, small and large R&D-oriented firms, and a range of TBED infrastructure functions, described below, which include skilled labor training through local community colleges, entrepreneurial training, small firm start-up support, and technology-focused financial infrastructure.[18]

Federal funding is typically supplemented by state financing. For example, in Pennsylvania, the state government provides funding, business and technical expertise, and access to a network of expert resources through the Ben Franklin Partnership Program.[19]

In summary, successful clusters all have similar characteristics, including selection of a technological focus that has high economic potential, a university at the core of the cluster's research infrastructure that provides both skilled workers and research support, entrepreneur training and company startup facilitation, and venture capital financing oriented toward the cluster's technological focus.

Innovation Districts

As previously discussed, the growing complexity of emerging technologies increasingly requires the co-location of technology-based economic assets to facilitate information sharing, resource sharing, and risk pooling. Such co-location synergies have driven the evolution of more concentrated technology-based ecosystem, in particular, innovation clusters.

However, just as the cluster concept has become mainstream in TBED policy environments, even more comprehensive ecosystems are appearing. One of these is the "Innovation district," which is an elaborate form of an innovation cluster. This term describes distinct locales where high-tech companies, including startups, interact with an array of research, management, and educational institutions from universities to accelerators and incubators. Katz and Wagner (2014) characterize innovation districts as a new complementary model of technology-based growth in geographic areas (typically urban) where leading-edge "anchor" institutions and companies cluster and connect with start-ups, business incubators, and accelerators.

[18] See Manufacturing Innovation Institute (MII) Program at https://www.manufacturingusa.com/. Specific MII's are described in multiple sections of this paper.

[19] See https://benfranklin.org/.

There is also a dynamic dimension to the concept of an innovation district in which a large number of both private and public funding sources drive the evolution of a research, education, and production ecosystem. Established companies are enablers, partners, and customers of the entrepreneurial-based startups and fast-growing small technology-driven companies.

Putting these attributes together, Katz and Wagner (2014, pp. 1-2) characterize the emerging role of innovation districts by the following:

> *"Innovation districts represent a radical departure from traditional economic development. Unlike customary urban revitalization efforts that have emphasized the commercial aspects of development (e.g., housing, retail, sports stadiums), innovation districts help their city and metropolis move up the value chain of global competitiveness by growing the firms, networks, and traded sectors that drive broad-based prosperity. Instead of building isolated science parks, innovation districts focus extensively on creating a dynamic physical realm that strengthens proximity and knowledge spillovers. Rather than focus on discrete industries, innovation districts represent an intentional effort to create new products, technologies and market solutions through the convergence of disparate sectors and specializations (e.g., information technology and bioscience, energy, or education)."*

The technical infrastructure of innovation districts is particularly noteworthy because it exhibits both concentrated forms, such as a research university, and more dispersed forms such as digital infrastructure. Further, some innovation districts such as the Seaport Innovation District in Boston are rigorously planned initiatives. As described by Baily and Motalbano (2018), Seaport is a "re-imagined urban area" that has transit access, historic building stock, and is close to downtown Boston. Unlike in many of the other case studies examined, no anchor university or dominant high-tech firm drove its evolution. Instead, the city has been the main driver.

Katz and Wagner (2014, pp. 2-3) define three forms of innovation districts:

(1) <u>"Anchor Plus" Model</u>. Found in larger cities, where major anchor institutions, primarily large research-intensive universities, attract entrepreneurs and startups, in particular, fast growing spin-off from universities or larger companies pursue the development and commercialization of new technologies. As examples, Katz and Wagner cite Kendall Square in Cambridge (anchored by MIT and other nearby institutions like Mass General Hospital), Philadelphia's University City (anchored by The University of Pennsylvania, Drexel University and the University City Science Center), and St. Louis (anchored by Washington University, Saint Louis University, and Barnes Jewish Hospital).

(2) <u>"Re-imagined Urban Areas" Model</u>. Often located in revitalized industrial or warehouse districts, built around advanced research institutions and anchor companies. Katz and Wagner cite Boston's South Waterfront, San Francisco's Mission Bay, Seattle's South Lake Union area, and the Brooklyn Navy Yard, as examples.

(3) <u>"Urbanized Science Park" Model</u>. Commonly found in suburban and exurban areas, which facilitate increased integration of technology-based assets and also offer life-style activities (such as retail and restaurants). North Carolina's Research Triangle Park, one of the earliest

traditional research parks, is cited as a standout example of the urbanization of traditional exurban science parks. Their new master plan calls for a greater concentration of research/corporate buildings and amenities, and even the possible construction of a light rail transit line to connect the park with the larger Raleigh-Durham region.

The impact of co-location synergies from the clustering of R&D facilities was estimated by Carlino and Hunt (2012) to be significant at short distances of about one-quarter mile, but such synergies quickly dissipate with increasing distance. One particularly important aspect of such synergies is the creation of pools of highly skilled workers.

Such synergies are increasingly important in the design of TBED strategies as technologies become more multidisciplinary in character and their system character becomes more complex.

7. TBED Policy Instruments—Support for Startups and Small Firms

The range of potential market applications from modern technology platforms includes opportunities with relatively small economies of scale and scope, which therefore offers significant opportunities for innovation by small firms. These firms, including startups, attempt to penetrate high-tech markets beginning in the early phases of a technology life cycle due to the numerous potential opportunities for innovative applications of emerging technology platforms directed at smaller, technologically dense market opportunities.

As pointed out by Hathaway (2016), institutional mechanisms exist to support the development of early-stage growth-oriented business ventures—incubators, angel investors, and more recently startup accelerators, which have evolved in recent decades to help startups during the vulnerable early stages in their lifecycles. Many of their supporting features overlap with each other, but individually each focuses on a different portion of the substantial set of “market failures” (economic barriers) to socially desirable levels of investment.

As Hathaway (2016) also observes, the proliferation of infrastructure policy instruments not only emphasizes the explosive growth of TBED policy initiatives by a majority of states but in the process has led to experimentation with a variety of forms of each instrument.

<u>Entrepreneurship Centers</u>

Entrepreneurship centers connect startups to sources of technical and “soft” business skills and provide networking expertise and assistance needed to start and mange high-tech businesses. As entrepreneurship centers have adapted and changed to meet the needs of their local communities, they have adopted new models of service delivery, expanded the services they offer, and seen shifting revenue streams.

As summarized by Duggins (2018) from an IMPACT Index Survey by the International Business Innovation Association, none of the centers surveyed are in an area with a population below 100,000, and most are in locations with significantly larger populations.

Academic organizations have a long history of close relationships with entrepreneurship centers, and many of the oldest incubators in the U.S. are affiliated with academic institutions to help provide a broader range of services. Universities and other post-secondary institutions continue to have a strong presence in the arena of direct support.

However, the majority of entrepreneurship centers operate on $500,000 or less in total revenue. As traditional sources of revenue become increasingly inadequate, a growing trend of collaboration and partnership with corporations is emerging. In fact, some entrepreneurship centers working closely with corporations are in buildings far from a main university campus and therefore do not interact with students or academic programs. As a result, some of staff or clients in this latter group may not even be aware of relationships these centers could have with academic institutions.

According to Duggins (2018), the majority of respondents (56 percent) to the IMPACT Index Survey operate on less than $500,000 in total annual revenue, including subsidies. In spite of relatively small budgets, Table 2 shows that several significant types of nonpecuniary assistance are provided through affiliations with high-tech companies:

Table 2: **Categories of Affiliations between Corporations and Entrepreneurship Centers**

(1) Provision of tangible assets or in-kind resources in the form of facilities or programs

(2) Collaborations by sitting on centers' advisory boards

(3) Vetting startup companies/ideas or providing startup funding

(4) Providing mentors and personnel

(5) "Other" such as primary funding for the center, providing pilot opportunities, and leasing space to the entrepreneurship center

These corporate relationships are indicative of an emerging trend. In fact, growing uncertainty regarding federal government funding (primarily from the Economic Development Administration) coupled with the emergence of corporate interest in entrepreneurship is steadily increasing reliance on non-governmental sources of expertise.

Some states are becoming more aggressive in providing broader support for entrepreneurship. The University of California's Office of Innovation and Entrepreneurship in the Office of the President of the University of California System has 49 entrepreneurship education programs, 33 incubators and accelerators, and 15 startups, proof-of-concept programs, initiatives, and competitions.

The System's top two industries are medical therapeutics and software and related services. 1,267 UC-affiliated startups were born between 1968 and June 2015; as of June 2015, 622 of these UC-affiliated startups were still active. Of these still-active startups, 447 have recorded employment of over 38,000 people. In 2016, the Office of Innovation and Entrepreneurship received $22 million to strengthen the entrepreneurial ecosystem in the state by developing the skills of entrepreneurs and by expanding the State's university system's network of external partners, both industry and government, to enable technology commercialization via partnerships and spinouts.[20]

[20] Based on presentation by Christine Gulbranson, Office of Innovation and Entrepreneurship in the Office of the President of the University of California System summarized in NAS (2018).

Startup Accelerators

As described by Clark (2014), a startup accelerator is an institutional mechanism that provides a young company guidance and resources to leverage growth in its size and value in order to "accelerate" the initial round of formal 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 support 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."

Startup accelerators have been a critical component in the creation of thousands of startups, including such familiar names as Airbnb, Twitch, Stripe, Dropbox, Twilio, Simple, Pluto TV and ClassPass. These startup-creation machines provide some combination of education, capital, co-working space, product-development support and access to a strong support network. They enable companies that are ready for venture capital to more quickly qualify and thereby attain financing (Patel, 2017).

Because of these important roles, it is not surprising that from 2008 to 2014 the number of US-based accelerators increased by 50 percent each year. Because of increased support for this TBED mechanism, the US remains No. 1 ranked with respect to startups aided, but other economies are accelerating similar support (Hathaway, 2016).

More specifically, Hathaway calculates that from 2005 to 2015, 172 US-based accelerators invested in more than 5,000 U.S.-based startups with a median investment of $100,000. Including follow-on financing, these young companies raised a total of $19.5 billion in funding during this period—or $3.7 million per company on average—reflecting leverage of the relatively small investments made in these early-stage companies by accelerators.

Clearly, as Hathaway (2016) also points out, "accelerators can have a positive effect on the performance of the startups they work with, even compared with other key early-stage investors, such as leading angel investment groups". However, this finding is not universal in that such positive impacts have been only attributed to leading accelerators. Outside of those, "the impact of participation in an accelerator may be ambiguous—or perhaps even negative."

One possible reason for this apparently skewed performance is that an *accelerator* works with a startup for a relatively short period of time, usually from 90 days to four months. Accelerators also receive on average modest amounts of capital, usually somewhere around $20,000. In return, the company frequently must give the accelerator institution an equity share in the company. Accelerators usually require anywhere from 3 to 8 or more percent ownership of a client company.

As a general policy mechanism, accelerators share the following five common traits (Izquierdo *et al*, 2016):

(1) An application process that is open to all, and is therefore highly competitive.
(2) Possible provision of pre-seed investment.
(3) A focus on small teams instead of individual founders.

(4) Time-limited support comprising programmed events and intensive mentoring.
(5) Cohorts or ‘classes’ of startups rather than individual companies.

With respect to (2), some better funded accelerators are now giving grants to startups, which, of course, means no loss of equity for the recipient. An example is an Austin, TX accelerator, which offered $500,000 in grants to local startups. The funding is being provided by an interesting financial infrastructure development—funding by a nonprofit (in this case, MassChallenge) that leverages corporate funding for local accelerator programs (O’Brien, 2017). The three top such nonprofits—MassChallenge, 500 Startups, and Techstars) funded a combined total of 888 startups in 2016 (Izquierdo *et al*, 2016).[21]

Within the U.S. economy, Hathaway (2016) points out that 54 metropolitan statistical areas spread across 35 states and the District of Columbia have accelerator programs. However, he also observes that the number of accelerator clients and financings are still concentrated in the oldest and most established TBED regions of San Francisco-Silicon Valley, Boston-Cambridge, and New York. These three regions account for about “40 percent of all accelerators in the United States, and almost two-thirds of accelerator-funded deals between 2005 and 2015.”

Technology Incubators

Incubators have been mentioned frequently in previous sections as one of the several important TBED policy mechanisms for enabling creative individuals to attempt to develop commercial versions of their ideas for new products or services.

According to OECD, technology incubators have three characteristics: 1) they should be technology-oriented; 2) they should have the potential to grow in a relatively short period of time and employ skilled workers; and, 3) they should closely involve graduates, often in applied sciences, in their management.[22]

Incubators are less structured than accelerators but have longer relationships with client companies. Mentorship periods often last over a year, as incubators focus less on quick growth and often seek only to prepare a company for an accelerator program. Incubators take little to no equity in client companies, as they do not provide upfront capital-like accelerators. Many incubators are operated by universities, which allows them to provide their services without charge.

Both accelerators and incubators often offer physical space for early-phase research. Equally important, as part of a larger TBED infrastructure, participation can provide startups with networking opportunities, which can facilitate next-round financing. However, as (Clark, 2014) points out, now that the startup is immersed in a larger infrastructure with its advantages of access to networking and exposure to sources of expertise, the institutional environment can impose reporting and more elaborate search costs that detract from actual technology development.

Large high-tech companies are beginning to use this mechanism to diversify their technology portfolios and ultimately penetrate new markets. An example is a $300 million tech incubator

[21] For a summary of the top seven accelerators, See Patel (2017).

[22] *OECD Innovation Technology Platform—Technology Incubators*, 2010. See http://www.oecd.org/innovation/policyplatform/48136826.pdf.

founded by United Technologies' Pratt & Whitney division. The company has created space for about 200 engineers, designers, and others in an attractive office building in New York City who want to develop new manufacturing concepts and to experiment with ways to solve problems affecting industry well beyond the aircraft industry.

The central rationale behind Pratt & Whitney's investment is to leverage commercial capabilities in rapid prototyping, iterative design, procurement, and testing to eliminate unnecessary internal barriers that slow development, stymie creativity and frustrate engineers. These broad application topics are inspired by the Pentagon's growing frustration with the 10-to 20-year development cycle for new engines and the current high development costs (Mcleary, 2018).

Technology incubators and accelerators have historically focused on software start-ups, due to that technology area's low R&D capital intensity and relatively short R&D cycle. However, a growing number are now supporting start-ups that are developing hardware technologies. The resources provided typically target assistance for the early-development stages, such as low-cost office space, developing business plans, and first prototypes (Singer and Bonvillian, 2017).

Innovation Orchards

As indicated above, a limitation of technology incubators and accelerators is that they typically only provide the modest resources to for early-development stages: low-cost office space, developing business plans, and first prototypes.

As Singer and Bonvillian (2017) point out, this institutional mechanism may be adequate for low capital-intensive technology development, such as software, which also have relatively short R&D cycles, but for more capital-intensive R&D that requires longer gestation periods, a more elaborate support mechanism is required that provides technical and financial assistance in later phases of the R&D cycle. Notably, large, mission R&D agencies, such as DoD and DoE, provide later-phase R&D financial and technical assistance, rationalized by the fact that the target technologies are aimed at providing a public good such as national defense or environmental quality.

However, for other technologies with large commercial markets as the target, these additional supporting policy mechanisms are just beginning to be applied. The most comprehensive implementation of a more comprehensive policy tool is the "innovation orchard," which is an institutional collaboration that constitutes, in effect, an "upgrade" to conventional technology incubators. Important areas for its application are capital-intensive technologies such as advanced manufacturing.

This policy mechanism integrates "university, industry, and potentially government partners to create an innovation infrastructure that provides start-ups with the know-how, access to technology, equipment, and bridge funding to get through R&D and then to scale up their new technologies for commercialization. The aim is to leverage strengths in a region's innovation system to help start-ups develop advanced prototypes, then demonstrate, test, and bring them to the manufacturing stage." (Singer and Bonvillian, 2017, p. 1). In effect, an innovation orchard substitutes direct provision of research assets for capital.

Although the Federal Government is justifiably criticized for not have a comprehensive and systematic innovation policy apparatus, it has nevertheless been instrumental in expanding support for critical TBED policy mechanisms that approach the innovation orchard concept. Its Manufacturing Innovation Institute (MII) Program is an example of support for a broader cluster-level innovation ecosystem with substantial potential impact of regional TBED performance.

Stated in terms of technology life cycle targeting, public-private partnerships are being created to advance radically new technologies through applied research that yields laboratory prototypes and thereby provide the product demonstrations necessary for startups to obtain venture financing for the development phase of R&D leading up to commercialization.

Singer and Bonvillian (2017) cite several examples of specific implementations of the innovation concept:

- *Cyclotron Road*. A program supported by the Department of Energy and its Lawrence Berkeley Laboratory, which offers advanced equipment to newly-formed energy-technology startups and assistance for applied research leading to advanced prototyping, demonstration, testing, and production design.
- *TechBridge*. A program of the Boston branch of the Fraunhofer Institute—a U.S. extension of Germany's famed nonprofit applied-research and development laboratory—that links start-ups with established private companies with whom can collaborate on late-stage product technology development, including the extensive laboratory support for new product validation necessary to de-risk start-ups' product technology development. Thus, TechBridge directly supports new technology development through industry partnerships that enable validation and demonstration of commercial prototypes—the last step before actual innovation (this is in contrast to Cyclotron Road where the client company performs these tasks independently).
- *The Engine. A*n aggressive attempt to integrate technology start-ups, large companies, federal labs, local incubators, and small- and medium-sized manufacturers within the Massachusetts regional economy. It offers laboratory space, technology, and expert consulting as a substitute for initial venture financing. One of the early implementations of this strategy is a collaboration between the Massachusetts Manufacturing Extension Partnership (MassMEP) and an area incubator, Greentown Labs, who together provide assistance to small area manufacturers and start-ups for production prototypes and pilot production. The rationale is that start-ups emerging from university labs have the requisite product research capability, but often lack manufacturing expertise. This program provides basic manufacturing knowledge and helps identify gaps and issues in client company manufacturing designs, which are aimed at facilitating partnerships between small regional manufacturers and start-ups at area incubators to create advanced prototypes and pilot production of initial products. Such scale-up techniques are typically a difficult challenge for research-oriented start-ups.

In summary, the provision of "innovation space" that offers advanced equipment, technologies, and accompanying expertise can reduce the need for venture funding in the early stages of the R&D cycle—which is becoming increasingly difficult to obtain. Through such innovation orchards, a start-up's technology can be sufficiently de-risked and development accelerated to get it to the commercial prototype stage where conventional venture capital is willing to come in.

Institutional Mechanisms for Providing Technical and Management Assistance for Small Firms

One of the infrastructure challenges for state TBED strategies is to provide technical assistance to small firms who typically lack the internal resources to search, find, and then assimilate new process technologies and management practices to enable them to grow to more sustainable sizes. As referenced at several points in earlier sections, a major Federal Government policy mechanism in this area is the Manufacturing Extension Partnership (MEP) Program, managed by the National Institute of Standards and Technology (NIST).

MEP affiliates are often intricately involved in state TBED ecosystems. For example, in the state of Washington, the MEP affiliate, Impact Washington, provides

- "Lean training"—cultures of continuous improvement and operational excellence
- Supply-chain consulting— step-by-step supply chain optimization strategies and critical-path mapping software
- Strategy planning—effective strategy formulation and implementation in today's high-tech manufacturing business environment[23]

Comprehensive TBED Policy Infrastructures

The above discussion of emerging policy models (particularly innovation clusters and innovation orchards) indicate that TBED strategies must be highly integrated ecosystems that enable companies within a cluster or orchard, especially small firms, to access different infrastructure resources as they evolve.

Although the concept of a comprehensive TBED ecosystem is just beginning to evolve, a few examples of such comprehensive policy infrastructures have been around for some time. The best known is Pennsylvania's Ben Franklin Technology Partners (BFTP).

As described by Parilla *et al* (2015), BFTP's overall role is to provide companies with capital, technical assistance, and networking connections within a regional economic environment. It makes direct investments to both start-ups and established companies seeking to commercialize new technologies. It has made over 3,500 investments in Pennsylvania companies since its founding in 1983. Often BFTP has been one of the first institutional investors in a company, providing critical risk capital and technical assistance that enable young startups to reach an inflexion point in their development at which point they are able to access conventional sources of financing, scale up production, and acquire needed skilled workers.

BFTP's experts also provide technical assistance in the areas of product development, marketing, fundraising, accounting, operations, and human resources—assets that are essential to reach and successfully pursue commercialization. An evaluation of BFTP by the Pennsylvania Economy League and KLIOS Consulting estimated that since 1989 the organization has contributed over $23 billion to the state economy, helped create 51,000 jobs in its client firms, and generated a 3.6-to-1 return on investment (Ben Franklin Technology Partners, 2013).

[23] For more detail, see https://impactwashington.org/.

Going forward, one of the logical areas for improved integration of policy mechanisms is the university role. As discussed earlier, once a source largely of basic science, the increasing globalization of science-based innovation has prompted attempts to improve the efficiency of the process by which the regional TBED ecosystem accesses and applies new scientific advances. Bayh-Dole is the prominent example of a policy mechanism aimed at the tech transfer efficiency imperative.

However, a number of universities have evolved much farther in terms of developing and integrating additional infrastructure roles in addition to technology transfer. Specifically, because universities also have business and technology management resources, it makes sense to provide such expertise to start-ups attempting to apply the university's scientific and technological advances.

MIT is an excellent example of this evolving integrated role. MIT's Technology Transfer Office has evolved well beyond the typical university TTO, which typically focuses entirely on generating licensing revenue. MIT's TTO emphasizes building relationships with spinoffs/startups and providing a wide range of direct support for eventual commercialization. [24]

Specifically, MIT has the following institutionalized services for startups:

- Venture Mentoring Service, which provides strategic and management advice from business and technology experts to alumni startups
- Entrepreneurship Center to educate students and assist them in starting companies through entrepreneurship courses in all of MIT's schools
- Despande Center that makes grants to entrepreneurial groups within MIT (faculty, researchers, students) to start companies based on new technologies

Many of these startups are nurtured through eight incubators located in the immediate vicinity of the MIT campus.

The combination of MIT's superior technology creation expertise and a much broader infrastructure for assisting spinoff companies has had substantial economic impact. Specifically, a Kauffman Foundation study by Roberts and Eesley (2009) estimated that

- An estimated 6,900 MIT alumni companies with worldwide sales of approximately $164 billion have been started and located in Massachusetts alone, which together represent 26 percent of the sales of all Massachusetts companies.
- 4,100 MIT alumni-founded firms are based in California, and generate an estimated $134 billion in worldwide sales.
- States currently benefiting most from jobs created by MIT alumni companies are Massachusetts (estimated at just under one million jobs); California (estimated at 526,000 jobs), New York (estimated at 231,000 jobs), Texas (estimated at 184,000) and Virginia (estimated at 136,000).

[24] William Bonvillian of MIT's Office of Digital Learning provided very useful information for this section.

An update to this study (Roberts *et al*, 2015)) found that the percentage of surveyed alumni who founded a venture within five years of graduation rose from 4% among those who graduated in the 1960s to approximately 8% among those graduating in the 1990s, and 11% in the 2010s. Moreover, many of these MIT entrepreneurs launched more than one company.

The latter study also found that a team-based approach to entrepreneurship was far superior to the traditional concept of the solo entrepreneur. In fact, most successful start-ups were co-founded by technologists and individuals who had marketing or sales experience (Roberts *et al*, p. 24). Such improvements in entrepreneurship training can greatly leverage the productivity of training programs across state TBED programs.

8. TBED Policy Instruments—Developing and Maintaining High-Tech Workers

TBED requires a highly trained workforce to design, manufacture, and operate high-tech hardware and software. According to Manyika *et al* (2017), advanced economies will find that the share of the workforce that may need to learn new skills and find work in new occupations will be as much as one-third of the 2030 workforce in leading industrialized nations such as the United States and Germany, and nearly half of the workforce in Japan. So, workforce training is an opportunity to create higher paid workers and a necessity for maintaining employment at any wage.

Analysis by the Brookings Metropolitan Policy Program (Muro *et al*, 2017) of more than 500 occupations underscores the rapid pace of growth in demand for digital skills. In fact, such skills are now a prerequisite for economic success in any regional economy.

For TBED planners, an important finding by the Brookings study is that, while the digital content of virtually all jobs has been growing, occupations in the middle and lower end of the skill spectrum showed the greatest increase in digital content. The report also finds that nearly 60 percent of tasks performed in low-digital occupations appear susceptible to automation, compared to only around 30 percent of the tasks in highly digital jobs. Thus, a broad-based education and training strategy is needed for long-term growth in addition to meeting the immediate needs of specific job categories associated with the current technological focus of target industries.

Further complicating this issue is an *OECD STI Policy Brief* (2015), which states that “on average across countries, roughly one-third of workers report a mismatch between their existing skills and those required for their job, implying they are either over- or under-skilled. This mismatch also represents a barrier to the growth of innovative firms. Making the most of the available skills in the economy requires reforms to policies that restrict worker mobility, and funding for lifelong learning”.

Some states, seeing both the need for skill training and the opportunity to help attract high-tech companies, have begun to upgrade their TBED-targeted educational infrastructure. For example, Katz and Muro (2014) cite South Carolina's Apprenticeship Carolina program, which supports on-the-job training. The state provides a tax credit to companies of $1,000 per year per apprentice and apprentices are paid while they learn on the job. Along with other such programs, this targeted educational infrastructure has helped thousands of workers find advanced industry employment.[25]

Similarly, the Tennessee Promise Program provides the opportunity for high school graduates to attend community colleges or technical colleges free of charge. In 2014, 53,000 high-school seniors (out of 71,000 statewide) signed up. Also, the Tennessee Labor Education Alignment Program helps coordinate skills training with available employer needs, and the state has a Skills Gap Grant Program that provides funding to regions to address shortfalls in needed skills.

The increasing digital character of virtually all industries and occupational categories within industries requires a range of new worker training approaches to support regional technology-based development strategies. As summarized by Muro *et al* (2017), states need

- A radical expansion of work-based training and recruitment
- Increased utilization of apprenticeships, co-ops, and internships to upgrade and expand IT skills
- Increased use of online and accelerated learning models that lower the cost of company-funded training
- Utilization of federal and state tax benefits for education assistance programs

Following countries such as Germany which use a “dual” (public-private) education model, greater use of company apprenticeships and paid internships that lead to IT certifications has been argued as essential to augment university computer science or engineering graduates. Clearly, the entire regional educational infrastructure must work together to promote certification-based IT learning in target economic regions (Muro *et al*, 2017).

An example of an American move toward the German “dual” education model is Kentucky’s automotive industry, which is the state’s largest manufacturing industry, employing 65,000 workers at over 400 facilities. As described in Parrilla et al (2015), Toyota, whose Georgetown plant is the company’s largest outside Japan, increasingly expressed concern that the region’s workforce infrastructure would not be able to upskill workers sufficiently and to replace increasing rates of worker retirements.

In response, the company partnered with the Bluegrass Community and Technical College (BCTC) to create the Advanced Manufacturing Technician (AMT) Program. The Program provides a multi-disciplinary degree focused on electricity, fluid power, mechanics, and fabrication, which collectively are designed to strengthen the supply of young skilled manufacturing workers in the Lexington region.

In many ways the AMT program resembles the German approach to dual-track training. Participating companies recruit from a pool of high school students that must meet a stringent set of requirements to be considered. The region’s educational institutions engage closely with

[25] For additional examples of workforce development efforts in individual states, see SSTI (2018). Most of these efforts appear relatively new and hence are not scaled up, but collectively they indicate growing intent across state governments to upgrade workers’ skills as part of a broader TBED strategy.

employers. BCTC has a facility on Toyota's campus so that selected students can get first-hand training with robots, computers and other equipment.

In January 2017, BCTC opened a $24 million Advanced Manufacturing Center (AMC), which will provide customized training in industrial maintenance, electronics, industrial electricity, robotics, mechanical drives, fluid power, and machining and welding. Unlike traditional community college campuses, the Advanced Manufacturing Center (AMC) is designed to mirror a manufacturing production facility. While containing classrooms, administrative offices, and computer labs, the bulk of the 78,000 square feet will be a "flexible high bay space" to provide training in an actual workplace environment.

Specifically, the layout is designed to provide a work environment similar to one where students will apply their skills after graduation. It is a partnership between BCTC and Toyota Motor Manufacturing Kentucky. The new center will provide a permanent home to the Advanced Manufacturing Technician (AMT) program that is currently being housed onsite at the Toyota facility.[26]

This overall educational infrastructure is a unique example of regional collaboration because it is entirely employer-generated. After developing AMT, Toyota helped regional manufacturers with similar talent needs pursue similar educational strategies, especially those making up their supply chain.

9. Technology Infrastructural Trends Affecting TBED Roles

The range of TBED programs discussed in previous sections are regional growth policy responses to a set of ongoing trends in the rate and directions of technological change, global competition, and economic growth policy philosophies at the federal and state levels. However, these policies cannot function in a vacuum. The development and implementation of TBED policies to support specific stages of a technology's life cycle must include access to a highly sophisticated technology infrastructure.

An iterative relationship exists between modern technologies and the supporting technical infrastructure. Such infrastructure, which exists at the regional, national, and global levels, has a life cycle character to it, just as technologies do. Thus, a specific technical infrastructure will evolve over time and interact recursively with various technology life cycles.

Occasionally, a major shift in technical infrastructure occurs to which the set of regional TBED policies must adapt. A current emerging example is the Industrial Internet of Things (IIOT). In essence, this paradigm shift is dramatically restructuring technology-driven supply chains; i.e., sets of connected industries. Specifically, the growing ability to exchange vast amounts of information between not just companies but directly between products and their developers—even after such products have been sold—has drastically increased the need for high-speed Internet infrastructure.

In the past, when companies in one industry sold a product to companies in another, the relationship between the manufacturer and the user largely ended. The user took over

[26] See https://www.wtvq.com/2017/01/04/bctcs-advanced-manufacturing-center-opens-january-9/ and http://legacy.bluegrass.kctcs.edu/photos/georgetown/.

responsibility for use and maintenance, as well as any updating that became available.

However, looking ahead to Industry 4.0/IIoT, products are increasingly being designed with internal sensors that monitor performance and relay performance status data over the Internet to the product's manufacturer. This enables the manufacturer to determine maintenance requirements and periodically update internal software to enhance the product's performance.

Further, as state TBED strategies tend to focus on a particular area of technology, it is imperative for resident firms to have access to a range of technical infrastructure that greatly enhances the productivity of R&D, production, and commercialization. For example, several of the current set of 14 MII's have a technological focus on advanced materials. During the Industrial Revolution, the typical material input was relatively simple. Today, so-called "advanced materials" are far more complicated.

For example, a recent study performed by RTI International for the NIST described a wide range of data bases, computational tools, and measurement/testing methods that advanced material industries depend on to raise rates of innovation and subsequent market penetration. Industry surveys emphasized the public-good content of this infrastructure. For example, nonproprietary data such as a repository of measured basic properties of materials are essential to industry for traditional R&D, and they now also validate the increasing use of computational models, which can significantly reduce R&D time and expense (Scott *et al*, 2018).

Yet companies have weak incentives to direct their experimental groups to generate this kind of basic data, as the cost and time for development exceed the use by any single firm. Moreover, developing a general architecture and tools for model validation and uncertainty quantification requires a combination of statistical analytic and materials engineering expertise surpassing what is typically required by the business model of any one company. Even when the multidisciplinary expertise does reside within a company, it has a weak incentive to develop and disseminate general-purpose tools and methods because is difficult to capture an adequate rate of return; that is, such tools and methods have strong public-good content.

In addition, for customers in a user industry in a high-tech materials supply chain to believe suppliers claims of superior performance, the materials characteristics data driving the computational models must have a level of validation achievable only through a collective development and validation process.

The Institute for Advanced Composites Manufacturing Innovation (IACMI), discussed in Section 5, is an example of a modern TBED entity that benefits greatly from such advanced materials infrastructure. Providing such technical infrastructure to support a cluster's R&D and commercialization efforts can have substantial impact. The NIST study estimated that the potential economic benefits of an improved Materials Innovation Infrastructure are between $123 billion and $270 billion per year (Scott *et al*, 2018).

This important implication for the enhancement of regional TBED policies is that an overall "connectedness" must be provided and that part of the "connected" infrastructure will be technically advanced tools and data that enable various policy initiatives to achieve maximum economic impact.

And, of course, the key element of connected technical infrastructure is digital communications. To enable the growing volume of high-speed communication between provider and user of high-tech products and related services, high-speed Internet infrastructure is essential, if a state TBED strategy is going to yields results across an entire state.

However, most states are limited in the potential geographic scope of TBED due to lack of adequate communications infrastructure. For example, whereas the state of Washington has achieved high rates of TBED in the western half of the state (one of the most technology-intensive regional innovation clusters in the US), the eastern half is actually experiencing population declines due the lack of private-sector investment and hence jobs. Much of this area has minimal Internet capability.

10. The Economic Impacts of TBED Programs

The general perception among policy makers and even most economists is that because technology is the main driver of long-term economic growth, the dominant policy variable is the amount of investment in R&D. Therefore, the supposition is that if the R&D intensity of an economy is increased, so will the rate of growth and also the rate of increase in personal incomes.

Fig. 3 shows that, in fact, a positive relationship exists between *business* R&D intensity and per capita GDP for the majority of state economies. The four states in the upper left-hand portion of *Fig. 3* achieve high per capita incomes with very low business R&D intensities. This is due to a strong reliance on combinations of natural resources and agriculture. As long as the global markets for the particular natural resource endowments in each state remain strong, this economic growth strategy will work. Similarly, Hawaii has, in addition to a significant agricultural sector, a huge and very profitable tourist industry and can do quite well through reliance on these two sectors.

Most states, however, must pursue a different growth trajectory to raise incomes over time—one that relies on productivity growth driven by investment in technology *and* a supporting technical infrastructure. In the face of globalization and the consequent increased competition in traditional goods and services, productivity can only be increased through sustained investment in technology and its three supporting assets.

The policy problem is that technology cannot be efficiently developed and effectively used in commercial applications simply be subsidizing private-sector R&D. While the relationship, as indicated in *Fig. 3*, is positive, the discussion in previous sections demonstrates that the efficient development and commercial application of new technologies requires an elaborate ecosystem, which provides not just resources but also a varied institutional infrastructure that can (1) raise the efficiency of the business R&D investment and subsequent scale-up for production and commercialization, and (2) provide funding for the earlier, higher-risk phases of the R&D cycle. These factors are collectively driving state TBED strategies in the form of a coordinated public-private asset investment model. [27]

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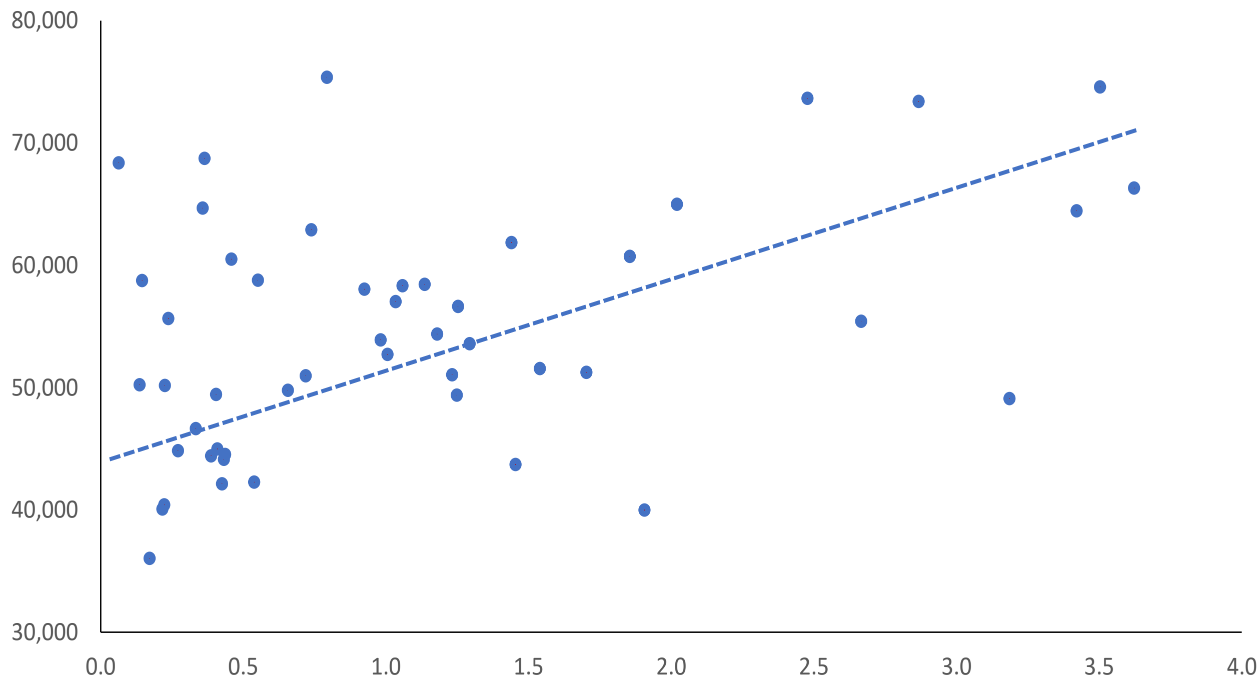
[27] For example, Block and Keller (2008) find that, whereas 80 percent of award-winning innovations were developed by firms acting entirely on their own in 1970, by 2006 over two-thirds of firms producing award-winning innovations benefited from federal-funding.

Fig. 3 **State Per Capita GDP vs. Business R&D Intensity**



Source: Bureau of Economic Analysis and National Science Foundation

As the earlier discussion using the Technology Element Model (*Fig. 2*) indicates, modern technologies evolve in stages and the nature and ratio of public- to private-good content varies by stage. Thus, so must selection and application of policy tools. Appropriate selection and application of policy tools makes a substantial difference in the subsequent rate of economic growth.

For example, an analysis by Howell (2017) using data on ranked applicants to the U.S. Department of Energy's SBIR grant program found that an early-stage award approximately doubles the probability that a firm receives subsequent venture capital and has large, positive impacts on patenting and revenue. Such grants, by focusing on the early-phase technology proof-of-concept (platform) development contribute significantly to the commercialization of new technology platforms created through the regional innovation cluster model.

To summarize previous discussions, the required assets for successful TBED include

(1) Both public and private R&D capability,

(2) An educational infrastructure for both research and production workers,

(3) A business culture and associated infrastructure that encourages entrepreneurial activity and associated creation of new R&D-intensive companies,

(4) A financial infrastructure that can efficiently provide risk capital, and

(5) An informed government bureaucracy that can provide overall policy guidance and resources.

This complexity of the evolving TBED policy infrastructure is reflected in emerging policy frameworks. By far the most comprehensive characterization and measurement of today's multifaceted TBED-related economic activity is the *State New Economy Index (NEI)*, compiled by the Information Technology and Innovation Foundation. It uses 25 separate indicators to characterize and rank states with respect to their relative investment and performance in TBED as the increasingly essential engine of growth (Atkinson and Wu, 2017).

Table 3 **The 25 Metrics for ITIF's *New Economy Index***

Information Technology Jobs	Managerial, Professional and Technical Jobs	Workforce Education	Immigration of Knowledge Workers
Internal Migration of Knowledge Workers	Manufacturing Value Added	High-Wage Traded Services	Foreign Direct Investment
Export Focus of Manufacturing	High-Tech Exports	Business Churning	Fast Growing Firms
Initial Public Offerings	Inventor Patents	Online Agriculture	E-Government
Broadband Communications	Health IT	High-Tech Jobs	Scientists and Engineers
Patents	Industry Investment in R&D	Non-Industry Investment in R&D	Movement toward a Green Economy
Venture Capital			

Source: Atkinson and Wu (2017)

The metrics used to compile the *NEI* are listed in *Table 3*. ITIF groups these 25 metrics under five major categories:

(1) Knowledge jobs: Indicators measure employment of IT professionals outside the IT industry; jobs held by managers, professionals, and technicians; the educational attainment of the entire workforce; immigration of knowledge workers; migration of domestic knowledge workers; worker productivity in the manufacturing sector; and employment in high-wage traded services.

(2) Globalization: Indicators measure foreign direct investment; export orientation of manufacturing and services; and the share of each state's output that goes to high-tech goods and services exports.

(3) Economic dynamism: Indicators measure the degree of business churn (i.e., the percentage of new business start-ups and failures); the number of fast-growing firms (businesses listed in the Inc. 5000 index); the number and value of initial public stock offerings by companies; and the number of individual inventor patents granted.

(4) The digital economy (information infrastructure): Indicators measure Internet and computer use by farmers; the degree to which state governments use information technologies to deliver services; adoption rates and speed of broadband telecommunications; and use of information technology in the health care system.

(5) Innovation capacity: Indicators measure the number of jobs in high-tech industries such as electronics manufacturing, telecommunications, and biomedical industries;

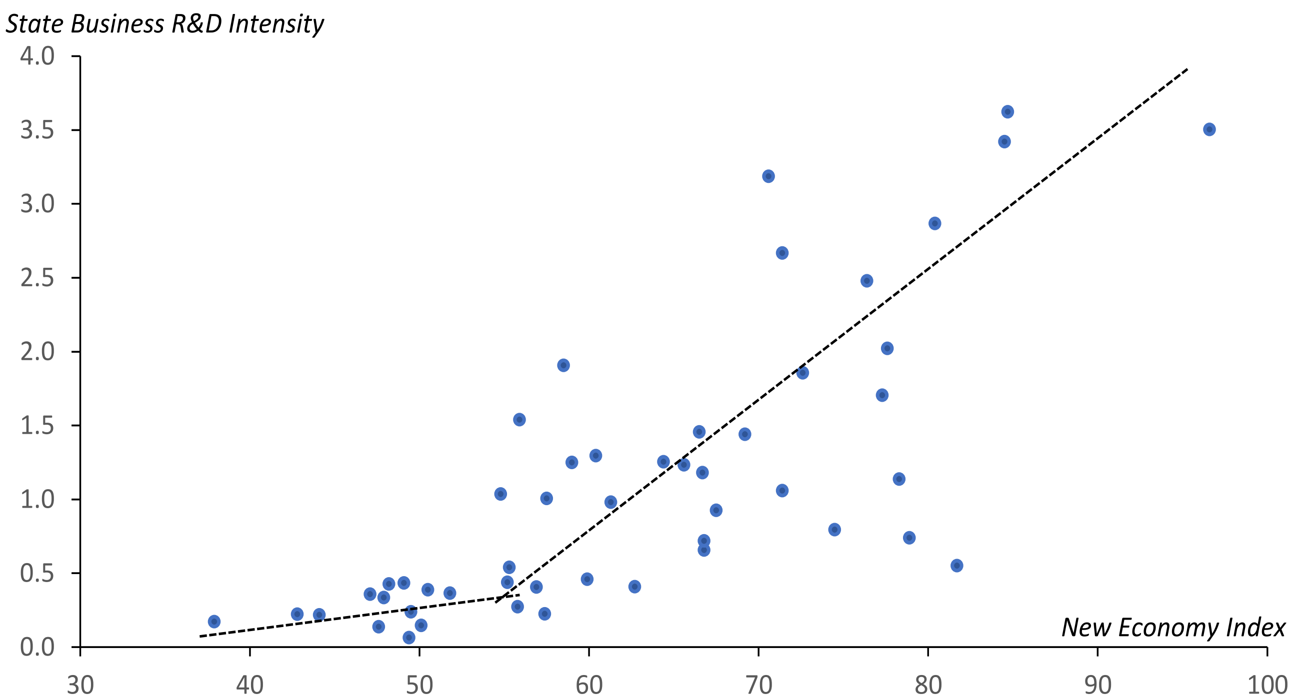
the number of scientists and engineers in the workforce; the number of patents granted; industry investment in R&D; non-industry investment in R&D; movement toward a clean energy economy; and venture capital investment.

As discussed above, a state's business R&D itensity certainly is an important summary determinant of state per capital GDP. However, the number and broad scope of indicators making up the NEI imply a complex set of determinants of the productivity of businesses' R&D investment. That is, industry's incentive and ability to invest in R&D is strongly influenced by the entire range of support mechanisms provided by TBED policies.

Fig. 4 indicates that this is the case. States ranking above a threshold *NEI* level of about 60 (greater investments in a wide range of TBED enhancing assets) experience a higher growth rate in business R&D intensity. This is a clear validation of the public-private asset model characterized in this paper as the driver of TBED.

Thus, contrasting *Fig. 3* and *Fig. 4* is extremely important for understanding the cause and effect of the many elements of emerging TBED strategies on attracting high-tech businesses and their higher income jobs. The major policy point is that, while business R&D is the direct driver of technology development, subsequent commercialization, and thereby economic growth, both the

Fig. 4 **State Business R&D Intensity vs. New Economy Index Ranking**

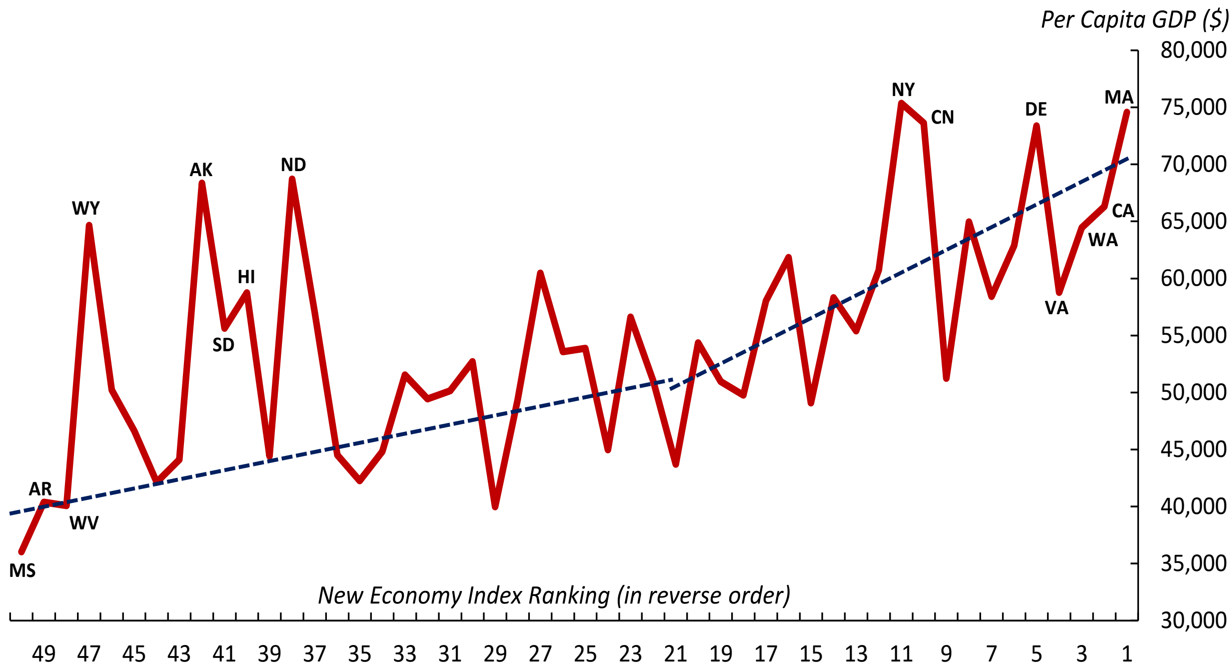


Source: ITIF for *New Economy Index* and NSF for state business R&D intensity

amount and the productivity of this R&D is significantly influenced by a large number of public and private investments that enable and enhance the process of private R&D investment and subsequent commercialization of new technologies. These investments include public sector R&D, which along with the large number of other "new economy" investments (*Table 3*) drive the productivity of business R&D and ultimately per capita GDP, which is the bottom-line metric for growth in corporate and worker income.

The logical final step, therefore, is to compare state per capita GDP to the *New Economy Index*. This is done in *Fig. 5*. The five states with low rankings but nevertheless high per capita GDP (Wyoming, Alaska, South Dakota, Hawaii, and North Dakota) have non-TBED growth strategies. They are are highly dependent on natural resources (plus tourist services for Hawaii). As long as the global demand for these states' particular endowments of natural resources remain strong, they can ignore the imperative to respond to the increasingly global technology-based economy. The fifth state, Hawaii, has a dominant tourist sector to drive the State's GDP.

Fig. 5 **State's Per Capita GDP vs. New Economy Index Ranking**



Source: Bureau of Economic Analysis and the Information Technology and Innovation Technology Foundation

The most important message for state policy makers is that the top 20 ranked states show a stronger response to higher *NEI* rankings, indicating that economies of both scale and scope exist with respect to TBED investments. That is, the per capita GDP response to greater investment intensity increases at higher NEI rankings, as indicated by the greater slope of the right-hand portion of the per capita GDP trend line.

Atkinson and Wu (2017, pp. 13-14) point out that the diversity of assets comprising the 25 indicators representing the TBED economy is a critical characteristic, as states can choose TBED strategies that emphasize different subgroups of assets and thereby establish niche comparative advantages. In this regard, they demonstrate how the top ten states in ITIF's New Economy rankings depend on different technology and market strategies that, in turn, drive different investment patterns:

(1) **Massachusetts**' economy emphasizes software, hardware, and biotech firms that are supported by world-class universities.

(2) **California** excels in innovation capacity, due to a large degree to Silicon Valley and high-tech clusters in Southern California. The state also continues to dominate in venture

capital, receiving 55 percent of U.S. venture investments, and it ranks highly for indicators of R&D, patents, entrepreneurship, and workforce skills—in other words, a comprehensive TBED strategy.

(3) **Washington State** ranks in the top five due to its strength in software and aviation exports, and also because of the entrepreneurial activity that has developed in the Puget Sound region, especially in biopharmaceuticals.

(4) **Virginia,** by virtue of its proximity to Washington, DC, attracts high-skilled workers for the numerous R&D-focused firms in the region, many of which supply information infrastructure services to the Federal Government.

(5) **Delaware** depends on a business-friendly corporate law environment that attracts both domestic and foreign companies and supports a high-wage traded services sector.

(6) **Maryland** has a high concentration of knowledge workers, many employed with the federal government (NIH) or with contractors supporting the federal government.

(7) **Colorado** has the third-most highly educated workforce in the country. In addition to its high scores on knowledge-employment indicators, the state also has become a focus for high-tech innovation in the middle of the country, and has a dynamic industry structure, evidenced a high rate of initial public offerings.

(8) **New Jersey** has a large pharmaceutical industry and has at least a number of the elements of a high-tech cluster centered on Princeton University and an advanced services sector in the northern part of the state; it is an above average destination for foreign direct investment.

(9) **Utah** leads in "economic dynamism" created by synergies among a strong high-tech manufacturing cluster centered in Salt Lake City and Provo, software/Internet services firms, and its ability to attract venture capital.

(10) **Connecticut** excels in traded services, employing a highly educated workforce, and receiving high levels of foreign direct investment.

A critical point is the fact that success breads success in that, once a threshold level of high-tech economic activity is established, private investment in the local economy is leveraged by the availability of a large labor pool. Management of this high-tech labor force is enhanced by the fact that educational institutions can rationalize a more extensive curricula and research/training facilities. More broadly, a fully developed TBED economy creates both economies of scale and scope in research, education, and technical infrastructure.

For example, research hubs/clusters/orchards promote economies of scope in research and therefore are attractive to R&D-intensive companies. In 2015, Toyota established an R&D enterprise in Silicon Valley. Called the Toyota Research Institute Inc. (TRI), this R&D enterprise is initially focusing on artificial intelligence and robotics.[28] The stated objective of TRI is to help bridge

[28] Toyota is also providing research funding directly to Stanford University, which is part of the Silicon Valley cluster. A second facility was subsequently created near MIT in Cambridge, MA. See https://newsroom.toyota.co.jp/en/detail/10171645/ and

the gap between fundamental research and product development; i.e., to bridge the so-called "valley of death"—the transition barrier between scientific advances and the initial phase of their applications in the form of new technologies. Toyota's location criteria including access to a leading research university and a large and diverse skilled labor pool.

11. Summary

Economic studies have conclusively shown that technology is the key driver of long-term economic growth. Yet, U.S. growth policies are not sufficiently oriented toward this critical investment and its supporting economic assets. State governments are attempting to at least partially fill the void with expanded TBED policies.

The need for expanded TBED is simple: high-tech workers are paid much more than the average worker. Thus, government officials at all levels should be doing everything possible to increase investment in technology-based economic activity.

To this end, the purpose of this paper is the demonstration of the complexity of technology-driven economic growth and hence need for a comprehensive TBED strategy composed of interacting policy elements. In particular, the complexity dimension mandates regional specialization and comprehensive support for private-sector investment over the entire technology life cycle.

Collectively, these economic metrics described in the previous section explain a regional economy's growth rate. Without considering all of them, policy makers fall into the trap of assuming that because R&D is the investment category that directly drives technological innovation and subsequent commercialization, one could view R&D conducted within the state for economic growth purposes by a few large firms as the singular dominant driver of a state's economy.

In fact, the evolution of the technology-driven economy that once depended upon both large, vertically integrated companies to conduct a dominant portion of the R&D necessary to deliver the final product, now increasingly depends on a complex supply chain of medium and small firms, who specialize in particular components of the final technology system—all of whom do considerable R&D.

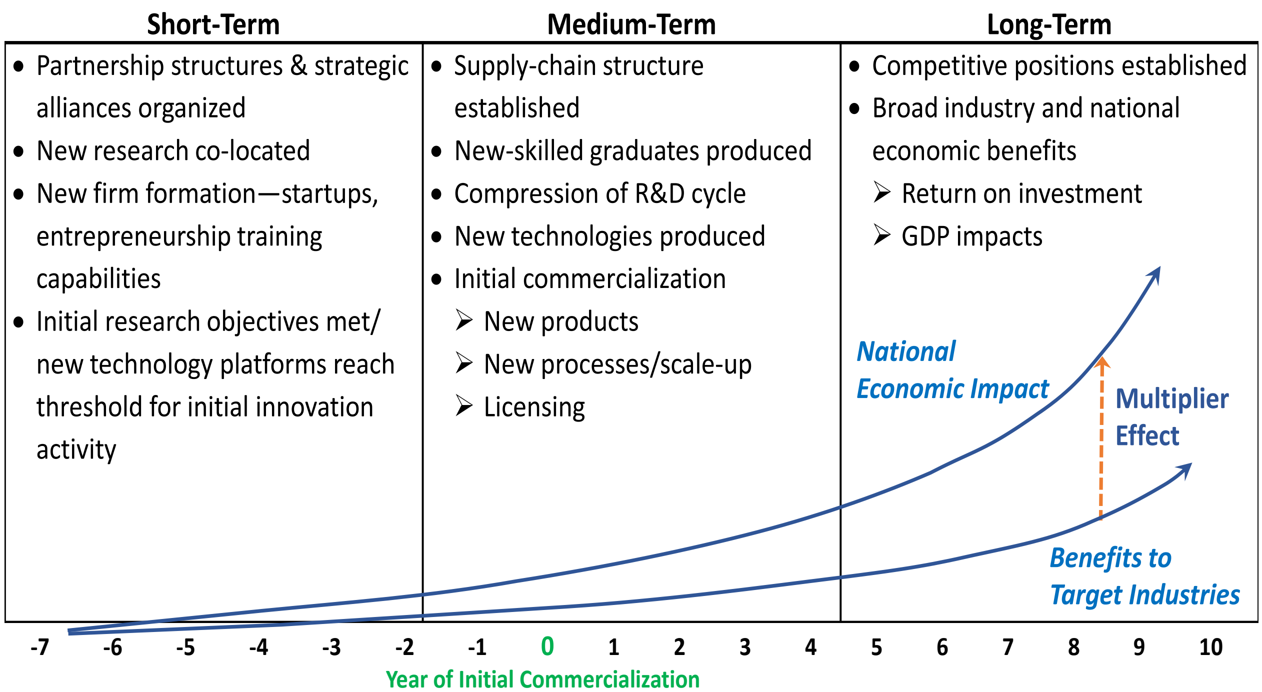
This increasing complexity greatly increases supply-chain coordination requirements, including the sharing of technical knowledge, joint technology and market planning (including with universities), and access to a heterogeneous pool of skilled labor. This situation begs the regional cluster model and places more responsibility on local TBED policy makers to provide needed infrastructure and financial support.

The need for a coordinated growth strategy among industry, state, and federal governments is further mandated by the complex public-private content of modern technologies, as evidenced by the sequence of steps over time required to turn science into commercially viable technologies. Fig. 6 shows a generic timeline for the set of steps required to make TBED the dominant economic

https://www.nytimes.com/2015/11/06/technology/toyota-silicon-valley-artificial-intelligence-research-center.html.

growth model. The typical timeline, especially for major innovations, requires patience and perseverance.

Fig. 6 ***Timeline for Economic Impacts from a Comprehensive TBED Strategy***



Adapted from G. Tassey, "**Beyond the Business Cycle: The Need for a Technology-Based Growth Strategy**," *Science and Public Policy 40:3* (2013)

Without recognition of the existence of the complex public-private growth model described here, simplistic economic growth strategies based solely on stimulating private-sector R&D through tax incentives, implying that raising R&D intensity is the only legitimate policy target, will continue to dominate national growth policy. Even to the extent that government funding increases so as to reverse its trend as a decreasing as a share of GDP, the fact that virtually all of this spending is for specific missions (defense, space exploration, health, clean energy, etc.) will constrain economic growth.

Further, as stated repeatedly in this paper, direct support for technology development is only one of four major policy targets. Technology is only put to economic use through "fixed" investment in hardware and software. Also, both types of investment (R&D and hardware/software) require skilled labor, which is both correctly trained and mobile. Finally, the entire TBED process requires a set of technical infrastructures to enable R&D, effectively use new technology, and mange market penetration strategies.

Thus, the achievement of high sustained rates of technology driven economic growth requires (1) R&D portfolios and funding mechanisms that respond to the complexities of technology development for commercialization in the face of increasingly intense foreign competition, and (2) the complementary set of public and private economic assets that facilitate the entire technology life cycle (technology development, scale-up for commercialization, and actual market penetration). The complexity of the require set of economic assets is reflected by the fact that ITIF's "*New Economy Index*" contains 25 separate metrics. Collectively, they reflect the productivity and hence the competitiveness of state economies and, in aggregate, the national economy.

Because of both greater complexity and the need for technological diversity, a regional TBED strategy approach is an attractive national strategy. Unfortunately, as stated by Muro and Katz (2010), "the federal government has not historically viewed regional competitiveness as an important foundation for national economic well-being and has instead concerned itself with what might be called the 'macro' and the 'micro.'"

The bottom line is that, in the past several decades, the growth in the inflation-adjusted (real) incomes of American workers has declined significantly. Changes in reals wages indicates changes in ability to consume and hence in the standard of living, so economic growth policy must relentlessly reflect this policy target.

The cause of this shrinking of the rate of U.S. economic growth is a slowdown in productivity growth. Because productivity is a metric for the efficiency of the transformation of economic inputs into outputs, its level determines the level of workers' incomes. That is, companies pay for productivity, so raising it is the only way to improve the welfare of an economy's workers.

To varying degrees, other industrialized nations have adopted and are, in fact, expanding regional-based growth strategies (Tassey, 2018b). As this process of technology-based economic convergence unfolds across the world's economy, addressing this policy mandate can no longer be left to the misguided and out-of-date economic growth philosophy that individual entrepreneurs and even large companies can succeed independently in a technology-driven economy where the United States accounts for only 4.5 percent of global consumers. This means 95 percent of the world's consumers live outside this country. Other economies are targeting global markets with ever increasing resources provided by both their domestic industries and their governments. In today's world, governments compete against each other as much as do their domestic industries.

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