Nurturing the Growth of a National Infrastructure in Emerging Technologies

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I. BACKGROUND

A fundamental responsibility of the leadership of a sovereign government is to create policies that enable the overall wellbeing of its citizens. This responsibility has many dimensions but certainly wealth generation through industrial competitiveness is a key component. Today a nation's economic strength rests not only on ownership of saleable natural resources but increasingly on the technical capabilities and innovation capacities of its citizens. This is particularly true in an environment where technologies are constantly emerging to serve as the foundation for new industries. How does a relatively small nation-state, but with significant resources and aspirations, compete and excel in this environment? This article briefly describes an approach taken by the Abu Dhabi Emirate of the United Arab Emirates (UAE) to foster national competitiveness in selected emerging technologies

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in which the nation had previously had very little presence.

It all began with a realization by the government of Abu Dhabi in the very early days of the 21st century that despite the substantial economic benefits of its petroleum-based industry, it would be critically important to diversify from this dominant economic base to other industries. In 2007, the Abu Dhabi Vision 2030 was cultivated to ensure the diversification and sustainability of a healthy economy so that the citizens of the UAE and its inhabitants would continue to have access to a high quality of living and rewarding style of life. Abu Dhabi's major global investment company, Mubadala, played a leadership role in implementing Vision 2030 and began to invest strategically in the diversification of the economy.

Initially, Mubadala undertook to study the various success factors that had enabled small nation states such as Singapore and Ireland to successfully develop industries that were internationally competitive. Quantitative metrics were developed which served as aspirational targets for the Emirate's economic diversification. The targets were developed to measure progress along a variety of dimensions including science and technology. Innovation in science and technology is no stranger to the Arab world. In the first millennium of the Common Era, Arab countries were a major contributor to breakthroughs in science and technology [1]. Scientists during this period built the foundations of modern mathematics, astronomy, chemistry, medicine, optics, etc. A few examples of the contributions of the Arabic Golden Age are given in Box 1. It is instructive to compare the Arabic "East" and European "West" in terms of the total number of publications (which will be used in this study as a measure of intellectual production). During 700–1000 A.D. the total number of manuscripts produced in the "West" is estimated to be around 270 000 [2] (about 1200 unique titles), which is in contrast with the book production in the "East," which exceeded 1 300 000 (about 6000 unique titles[1]). The driving force for the scientific and technological leadership was an active "patronage of scientific knowledge."

[1]The Catalog (Kitab al-fihrist) by Ibn al-Nadim published ca. 990 CE is an index of all books written in Arabic contains 5970 titles of books.

Box 1. Examples of scientific and technological production in the Arabic World ca.700-1000 CE

Chemistry — *Jabir ibn Hayyan* (721 – 815)

1st production of sulfuric and nitric acids

Mathematics — *Muḥammad al-Khwarizmi* (780 - 850)

Developed the "calculus of resolution and juxtaposition" (hisab al-jabrw'al-muqabala), more briefly referred to as *al-jabr*, which became today's **algebra**.

Astronomy — *Ali ibn Ridwan* (c. 988 - c. 1061)

Provided the most detailed description of the supernova SN 1006, the brightest stellar event in recorded history, observed in the year 1006.

Mechanics — *Ismail al-Jazari* (1136–1206)

Credited as the inventor of camshaft;

Built the 1stprogrammable automata (Al-Jazari's musical robot band).

Medicine — *Abu Al-Zahrawi* (936–1013)

Known as "the father of surgery". He introduced over 200 surgical instruments and pioneered many surgical procedure.

House of Wisdom

The House of Wisdom (Bayt al-Hikma) was founded in Baghdad during the reign of Caliph al-Mansur (754–775) and became a major intellectual center where many well-known scholars were invited to share information, ideas, and culture. The House was a center for the study of humanities and for science, including mathematics, astronomy, medicine, alchemy and chemistry, zoology, and geography and cartography. Scholars associated with the House of Wisdom accumulated a great collection of world knowledge, and built on it through their own discoveries. By the middle of the ninth century, the House of Wisdom had the largest collection of books in the world.

Rulers and wealthy urban groups funded scientific output and also established libraries and other institutions where scientific topics were studied, such as the House of Wisdom in Baghdad. This patronage was provided for both prestige and for the "practical benefits promised by the practitioners of medicine and astronomy and astrology and applied mathematics." This direct patronage system is to some extent equivalent to the modern funding system of science by governments and private organizations. Yet over much of the 20th century, the Arab world had fallen seriously behind in science and technology. Back to back stunning reports by the United Nations Development Programme (UNDP) in 2002 and 2003 revealed how far behind the Arab world had lagged in human development and knowledge production. For example, the number of frequently cited papers of active researchers was below 0.1 per million people as opposed to 42 per million people in the United States [3]. The Arab countries in total had generated less than 500 patents registered in the United States as compared to over 16 300 for South Korea during a 19-year stretch from 1990 to 1999 [4].

These UNDP reports truly shocked the Arab world and served as a wake-up call for action. Many responded to the challenge and the UAE was at the forefront of developing the necessary systems and infrastructure for knowledge production. In particular, Abu Dhabi's Vision 2030 in 2007 set forth an important roadmap for reversing the downward trend of the region in science and technology.

The vision identified priority areas for economic development and set output achievement targets for education, healthcare, and various economic sectors. Abu Dhabi began a massive effort to build strong foundations in education, beginning with major reforms in K-12 and higher education. The ultimate goal was to diversify the economy through innovation and knowledge production.

II. CHALLENGES

Building innovation capacity in science and technology (S&T) requires a full ecosystem of human capital development, R&D funding, a culture of entrepreneurship, and startup and commercialization pathways, enabled through both government and private sector support. Building and sustaining such an ecosystem is an enormous undertaking not just for a young nation like the UAE, but for any nation. The challenges for Abu Dhabi included: attracting top human capital capacity in S&T; building local human capital capacity, aligning the output of higher education with the needs of the industries under development at the time; funding R&D on a larger scale; and developing pathways to productization and commercialization. Each of these challenges is major in itself, let alone considering all of them together. This resulted in yet another challenge: convincing the key people and especially the prospective faculty that it can be done.

There were also additional challenges that developed over the course of the program. Many of them were typical challenges that any R&D program faces such as continuity of the research in the face of graduating students and typical faculty turnover. However, when building a program from scratch, combined with an insufficient pool of potential faculty to recruit locally, the challenges are exacerbated. A loss of even one faculty member would cause major delays for the program. Thus retention becomes even more of an issue and appropriate mechanisms must be in place to minimize turnover.

III. STRATEGY

In developing the strategy, it was important to learn from the experiences of other nations but it was critical that such learning be done in the context of Abu Dhabi. It was recognized early on that one cannot take a strategy that worked in one country and make it work in another with a different set of constraints and capabilities. A tree that flourishes in one environment may not see the light of day in another. For example, both Singapore and Ireland (two of the key benchmark nations) started from a different R&D baseline than Abu Dhabi.

Building on the lessons learned from the benchmarking analysis, and given the particular needs of Abu Dhabi, the strategy for R&D that emerged rests on the following principles: 1) learn from other successful national endeavors, but leverage Abu Dhabi's strong resources to accelerate progress; 2) align R&D with priority areas of the economy; 3) bring industry, government, and academia together with unity of purpose; and 4) give priority to local human capital development. The R&D strategy was to develop applied research focused on a select few industry pain points. It was to begin by establishing a critical mass of researchers and then building scale over time.

To be successful, an R&D strategy must be one that can be implemented effectively on the ground. Resources are critical, but successful implementation on the ground often requires building the right R&D culture and nurturing this culture so that it can be sustainable if the availability of resources fluctuates over time. A failing strategy is often blamed on lack of execution, but in fact a failing strategy is most often one that is not well designed from the beginning because it failed to consider implementation realities. As one learns from benchmarks of success (Singapore, Ireland, and others), one must also learn from benchmarks of failure.

To maximize the chances of success, the strategy was built on areas of existing strength. One area of strength was a direct result of Mubadala's bold decision to invest heavily in semiconductor technology, beginning with the formation of Globalfoundries in 2008. Why this industry? There were several reasons but chief among them was the realization that semiconductor technology is the base upon which much of the burgeoning information technology industry rests. The semiconductor industry has served as the enabler of the technology boom that has changed the world. From mobility to social media, the semiconductor industry is the very foundation for the digital and knowledge revolutions that have touched the lives of people across the globe. However, in 2008, though the country was among the world leaders in deploying Information and Communication Technologies (ICT) infrastructure, scientific expertise in semiconductor technology, such as IC design and process technology, was virtually nonexistent in the UAE. To bridge the gap, and guided by the overarching R&D strategy, a plan was developed to build local capacity in semiconductor technology. The plan involved several accelerated phases, including endowed chaired professorships, lab infrastructure, student fellowships, and partnership with Globalfoundries. It also included developing a special partnership with the Semiconductor Research Corporation (SRC). SRC, an industry-led consortium of international companies, was engaged to organize and conduct a major Abu Dhabi university research program in semiconductor technologies, with a strong emphasis on engaging UAE nationals. This was the first major undertaking by SRC outside the United States.

SRC personnel met with the leadership and faculties of several of the larger universities, including Masdar University, Khalifa University, UAE University, NYU-Abu Dhabi, American University of Sharjah, and others to evaluate interest in semiconductor research. SRC also evaluated the existing curriculum in the UAE universities that was supportive of semiconductor technologies. There existed some salient courses but not very much depth in most universities. Another evaluation dealt with the semiconductor-related research output of UAE universities, and it was found that there was little international recognition as indicated by papers published, citations, patents, etc.

There was some initial skepticism among the faculty that SRC would actually fund university research programs; however, when solicitations were offered, the response was dramatic (there were 48 proposals to the first solicitation and seven were funded). A second challenge to initiating university research centered on the need to recruit UAE nationals to pursue graduate education in semiconductors. This was understandable since degrees related to, for example, the petroleum industry usually came with employment opportunities, whereas in the semiconductor industry, future employment opportunities were unknown. Early on, therefore, the UAE universities were in a highly competitive environment for recruitment of outstanding students. As a cultural and anecdotal observation, young UAE women seemed to respond very positively to opportunities for semiconductor education. In fact, contrary to what one might find in many other nations, women represent the majority of students in disciplines such as computer engineering at the federal universities. For example, in the 2016/2017 academic year, the total number of students enrolled in the College of Engineering at UAE's flagship federal university, The UAE University, was broken down as follows: 847 male students and 1825 female students (this is the total number of students and not particularly the number in the semiconductor program) [5].

Finally, as an adjunct to the basic UAE-based research program, SRC endeavored to link UAE undergraduate scholarship students studying abroad to existing SRC research programs in international universities.

IV. FINDINGS

The SRC operates by involving member company engineers and scientists as members of technical advisory boards (TAB) to plan, select, and evaluate each of its university research programs. The engagement of these TAB members in this process for UAE universities has been indeed exemplary. At each annual review, company evaluations are collected in several categories such as: 1) importance to my company; and 2) satisfaction with progress. Across the projects now funded in the UAE, the performance of researchers is now on par with the evaluation results obtained across the several hundred projects operational at SRC at any given time. For example, one of the major Abu Dhabi SRC centers funded by Mubadala began with a TAB score of slightly below the U.S. average after its first year of operation in a category related to the importance of the research, but ended its third year with a score at par with the best SRC-rated centers in the United States.

There are tangible results as well. For example, Table 1 demonstrates that overall scholarly productivity has substantially increased across key metrics that are especially relevant to the goal of increasing the UAE technical competence in the semiconductor sciences and technologies. The impact on graduate student enrolment is obviously significant given the growth of the semiconductor program over the period 2010–2016.

Indeed, all the numbers across the various categories in Table 1 are significant, but what is also noteworthy is the quality of the programs. Several of the research papers received best paper awards at major international conferences, and one of the papers was the most downloaded paper of the IEEE Transactions on Circuits and Systems in October 2016.

Finally, note that the two key universities involved in the semiconductor R&D programs were both very young universities in 2010 (for example, Masdar Institute was founded in 2007) and both experienced significant growth in other areas of engineering. Table 2 shows the overall growth in intellectual productivity measured over two intervals: 2007–2010 and 2013–2016. When compared to Table 1, it is clear

Table 1 Comparison of 2010 and 2016 Research Output by UAE University Researchers as Related to Semiconductor Technology R&D

2010				2016
3 MS	Students	PEOPLE	Students	100+ students graduated; 30 PhD, 23 MS
No Emiratis students	Students	PEOPLE	Students	3 PhD and 9 MS Emirati Students
3 Profs	Profs	PEOPLE	Profs	18 Profs
0	industry	PEOPLE	Industry	20+
1 refereed; 0 citations	Papers & Tapeouts	PUBS & TAPE-OUTS	Papers & Tapeouts	200+ refereed; 3240 In citations
1 TAPEOUT	Papers & Tapeouts	PUBS & TAPE-OUTS	Papers & Tapeouts	8 TAPEOUTS
1 Disclosed	Disclosed & applied	PATENTS	Disclosed & applied	23 Disclosed
0 applied	Disclosed & applied	PATENTS	Disclosed & applied	15 applied
0 issued	issued	PATENTS	Issued	3 issued
MIT, UC-San Diego, SRC, GF	Academic & Industry	PARTNERS	Academic & Industry	MIT, U-Manchester, ADNOC, TAKREER, STRATA, GF, SRC, A*Star, Berkeley

that much of the growth in citations can be attributed to the semiconductor R&D programs.

V. LESSONS LEARNED

Box 2 summarizes the seven key messages and lessons learned for quickly developing a green field (from scratch) R&D ecosystem. We would like to emphasize three points that may be subtle but important for rapid development of the R&D ecosystem. First, nations developing green field R&D have to set very clear priorities and initially focus on only a few sectors of the economy. Second, funding should be mostly directed toward industry pain points where an upstart program can be differentiated at the global level. While fundamental research cannot be neglected and has been a traditional focus at universities, the focus must shift toward solving real and practical industry problems. Third, the scale of coordination and collaboration among the three nodes of the triple-helix of government, industry, and academia must be very strong—even stronger than the coordination that exists in nations with highly developed R&D ecosystems.

Table 2 "Productivity" Growth of Abu Dhabi Universities [6]

		Masdar Institute	Khalifa University
2007-2010*	Total publications	48	35
	Total citations	24	3
	Average citation per item	0.5	0.09
2013-2016**	Total publications	1372	1579
	Total citations	6653	3917
	Average citation per item	5	2.5

*assessment made in March 2011

**assessment made in March 2017

Box 2. Key messages for rapid development of green field R&D ecosystems.

1. ***Clarity of Priorities***: Develop clear national research priorities with measurable targets
2. ***Singularity of focus***: Focus on a few sectors of the economy
3. ***Unity of Purpose***: Coordination between government, industry and academia must be made at a very deep level, even beyond what is typically practiced in nations with highly developed R&D sectors where such coordination is already quite strong.
4. ***Differentiation***: Place focus on a few industry pain-points where a difference can be made, and can provide differentiation in a relatively short period of time
5. ***Special Partnerships***: Developing solid partnerships with the best in-class is key to rapid development of R&D. In the case of the Abu Dhabi programs, the partnerships with SRC and Globalfoundries were essential.
6. ***Sustained Ecosystem Building***: Ensure that all aspects of the ecosystem are sufficiently funded and mutually supportive, including:
    a. Building the foundational laboratory infrastructure
    b. Establishing a few highly attractive faculty chaired positions. Great faculty attract other great faculty
    c. Building a pipeline of highly qualified students for sustainability
        i. Begin in high school with a focus on S&T
        ii. Fund undergraduate student research
    d. Focus on building critical mass via vertically integrated research centers
    e. Establishing the capability and clear pathways to productization
    f. Supporting spin-offs with flexible IP ownership/licensing policies
    g. Continuing funding at appropriate levels to sustain the research
    h. Ensuring flexibility: semiconductor technology is a very fast moving field. Strategies must be in place to make adjustments in the R&D strategy as needed to ensure continuity and relevance
    i. Measuring and Adjusting: a clear assessment system must be in place to assess the quality of the research and make appropriate adjustments
7. **Company as R&D Champion**: there must be a major private company that champions the research effort that is designed to quickly respond to its needs, and that accelerates the deployment of its results and innovations

It may be argued that the UAE is uniquely positioned, given its resources. Whereas such resources are very important, leadership is critical. In fact, it is the most important dimension. There are many nations rich in natural resources around the world that have not been able to substantially develop their knowledge systems. In fact, one can argue that nations without such resources but ones that have the right leadership and innovation culture can develop competitive economies through knowledge systems. For example, South Korea's GDP per Capita in 1960 was $158 (in current U.S. dollars), less than that of Ghana at the time (source: World Bank data archive). However, even with no substantial natural resources, the nation was able to build its knowledge systems and, today, it stands tall as one of the world's top manufacturing and knowledge economies. A key message is that success requires having the right leadership and the right innovation culture.

Abu Dhabi's success in building its semiconductor technology R&D ecosystem was possible because several critical factors came together at the right time and in the right way—from the vision of the leadership, to the launch of Globalfoundries and the deep involvement of the SRC. However, we should not lose sight of the people who made it happen: the students and faculty of the Abu Dhabi universities. By its nature, the semiconductor R&D program is multidisciplinary, bringing together faculty from engineering and the sciences. Thus, the growth of the semiconductor program impacted several colleges and departments (electrical engineering, computer engineering, computer science, and physics) and contributed significantly to the overall intellectual output of the Abu Dhabi Universities. ■

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