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ARPA-E and DARPA: Applying the DARPA model to energy innovation

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Abstract ARPA-E offers a new innovation institutional model to meet energy technology challenges. Because it is explicitly based on DARPA, this article reviews the noted DARPA approach in detail. Briefly citing well-known features of DARPA, it explores a number of important features that have not been well discussed in the policy literature on DARPA. These include DARPA's ability to undertake multigenerational technology thrusts, the synergies it has been able to create through complementary strategic technologies, its ability to build an advocate community, and connections it has built to larger innovation elements downstream from DARPA. It has also taken on incumbent technologies within both DOD and in the private sector, used ties to DOD leadership to press its advances, and supported initial market creation. The article then reviews the new ARPA-E model in detail, commenting first on how ARPA-E has adopted key DARPA approaches. It then discusses new features ARPA-E is adopting, driven by the unique demands of the complex, established energy sector. These include new ways: (1) to sharpen the research visioning, selection and support processes, (2) to build a community of support, important to its political survival, and (3) to implement technologies it supports. In addition, the further DARPA features enumerated above provide potentially useful future guideposts to ARPA-E. The paper closes with a discussion of the difficult technology implementation problems on the "back end" of the innovation system—including demonstrations, test beds, and initial markets. The article posits that both agencies must further address these implementation issues by fostering additional downstream partnerships, including between government and private sector.

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1 Overview

The United States faces powerful economic challenges in the interlinked and contradictory nexus of the economy, energy, and environmental issues. In this arena transformative innovation is understood to be a key public policy response (Weiss and Bonvillian 2009). One element of the response has been the creation of an energy-DARPA—ARPA-E.

DARPA was formed to address the problem of transformative innovation. Instigated in 1958 in response to the Sputnik shock, the Advanced Research Projects Agency (subsequently renamed the Defense Advanced Research Projects Agency) was created with an explicit mission: to ensure that the US never again faced a national security "technological surprise," like Sputnik, due to failure to pay adequate attention to and stay focused on breakthrough technological capabilities (Van Atta 2008; Bonvillian 2009a). DARPA itself can be categorized as a disruptive innovation, creating an approach to fostering and implementing radically new technology concepts recognized as transformational (Van Atta et al. 2003b).

Innovation is recognized as the linchpin for US economic growth,[1] transforming the economy based on new products that provide new economic and social functionality. DARPA was at the center of that innovation process in the second half of the 20th century, playing a keystone role in the computing and internet innovation waves (Ruttan 2006a). But the process of innovation aimed at such transformation is recognized as highly risky and extremely difficult to implement. In a complex innovation system laced with market failures between the stages of fundamental research and technology transition, governmental support increasingly has been viewed as a needed element. This risk and difficulty is captured in the term "disruptive innovation"[2]—where the potential novel capabilities offered by new innovations are impeded not only because they are new and different, raising unknowns and risks, but because they often entail the potential of disrupting existing markets, products, practices and approaches. They bring with them two "shocks": (1) they are sufficiently different that the existing system of investment and development is risk averse to them; and (2) in many cases they actually are seen as threats to vested products and capabilities, so they face further difficulty in achieving needed investment and support (Van Atta et al. 2003a). The threat and risk of such innovations are significantly expanded when they attempt to enter in complex, established legacy sectors such as energy (Bonvillian and Weiss 2009, 289–294; Weiss and Bonvillian 2011). Overcoming these double impediments requires strategically-focused technology development and management approaches.

[1] See, for example, Solow (2000), Romer (1990), and Jorgenson (2001).

[2] The term was developed by Clayton Christiansen, and reflects Schumpeter's economic concept of capitalism (Christiansen 1997). See, also, Schumpeter (1942) (concept of "creative destruction" in capitalism in which new technologies and processes create or alter firms and markets).

ARPA-E, the Advanced Research Projects Agency—Energy, was authorized in 2007 as part of the America COMPETES Act[3] and initially funded under the 2009 economic stimulus, the American Reinvestment and Recovery Act (ARRA 2009). ARPA-E was created to foster disruptive innovation in the complex, established legacy sector of energy, exactly the model described above. Although threatened by the partisan budget environment, ARPA-E obtained funding for FY2011 from Congress at close to the same level it was funded in the two previous fiscal years.[4] It has already emerged as a dramatically new model in the energy innovation space, worthy of in depth examination.

This paper looks first into DARPA as a model, asking a series of questions: What about DARPA has enabled its success? Is DARPA's success transferable to other arenas? In particular, this paper reviews less well-known features of the DARPA model not widely commented on to date. Secondly, the paper looks at ARPA-E, raising similar questions: Is ARPA-E designed to effectively emulate the DARPA model? Are there significant differences in the energy arena that inhibit or prohibit the success of this model? Are there new elements in the ARPA-E approach modifying and adapting the DARPA approach to increase ARPA-E's chance of success? Do some of the less well-known features of DARPA, as noted, provide lessons for ARPA-E?

There is an additional question behind this inquiry. What about DARPA and ARPA-E could or should be emulated by other organizations seeking to foster and effect transformative technological change? Both agencies represent a different model for technology advance. While standard model R&D agencies focus on research not technology, rely on a peer review process for selecting awardees, and do not use what could be called a technology visioning step in their process, DARPA, and now ARPA-E, reverse all these rules. They focus early in their processes on developing a vision of new technologies, then on developing a research program to achieve that vision, and on using empowered program managers, not a disparate peer review process, for award selections. DARPA's remarkable string of technology success has demonstrated the power of its model, and early successes at ARPA-E suggests it is dynamic and replicable. Features of this model may be of interest to other parts of the US R&D system. For example, the Department of Education and the National Science Foundation are considering an ARPA-Ed for education research, NIH is considering a translational research program, and the Department of Homeland Security and the intelligence agencies are working on implementing existing authority to form their own DARPA clones.[5] Thus, a careful review of the DARPA and emerging ARPA-E rulesets may offer lessons not only to each other, but to innovation ecosystems more broadly.

The paper then looks at a challenge faced by both DARPA and ARPA-E: technology implementation. Both agencies move technologies down the innovation pipeline to the prototype or small-scale demonstration stage. Neither agency has direct authority to enable

3 ARPA-E was first proposed in National Academies (2007, 152–157).

4 ARPA-E received $400m in initial funding from the 2009 stimulus legislation (ARRA 2009) for FY's 2009 and 2010; it did not therefore seek additional funding in FY2010, The Administration's budget sought $550m for ARPA-E in FY2011; Congress funded it at $180m for FY 2011 (Continuing Resolution FY 2011).

5 Attempts have been made in recent years in the federal government to create DARPA "clones," particularly HS-ARPA for the Department of Homeland Security, I-ARPA for the intelligence community and BARDA within the Department of Health and Human Services for biothreats and health emergencies. While there are questions whether these attempts successfully emulated DARPA, this paper does not specifically explore these organizations. HS-ARPA was never fully implemented; a number of the reasons, and implications for ARPA-E, are discussed in Bonvillian (2007a).

commercialization of its potentially breakthrough technologies. DARPA often relies on procurement programs by military services to form initial markets; ARPA-E has no counterpart to the services within DOE. How could this implementation hurdle be overcome? The paper concludes by reviewing this question, including a model at DOD for achieving this. Throughout the paper, drawing from detailed evaluations of both agencies, we discuss and make recommendations on the role of government in fostering transformative technology for energy and national security, including in the current and future world of globalized businesses, economies and technologies.

2 The DARPA model

2.1 Well-known elements in the DARPA culture

DARPA Deputy Director Ken Gabriel has suggested that several features central to DARPA are best explained by its name.[6] DARPA, (1) is not a broad research organization or lab but a "*projects*" agency pushing particular technology projects; (2) is primarily a "*defense*" agency that should take full advantage of its presence in DOD to move its technologies, and (3) works primarily on the "*advanced*" stage of breakthrough innovation not on incremental or engineering efforts that other parts of DOD focus on. This gives us a broad-brush portrait, but how does it actually operate?

Michael Piore has suggested that DARPA program managers exemplify a form of what are known in organizational literature as "street-level bureaucracies." Like cops on a beat or school teachers, or welfare caseworkers, the identity of line officers in bureaucracies, even one as creative and flat as DARPA, is best understood by the roles they play and the informal rules adopted by their colleagues in their professional communities. Piore writes,

> …in street-level bureaucracies, a series of tacit rules emerge which the agents apply in making their decisions. These rules grow out of the culture of the organization as it is shaped by the backgrounds… from which the agents are drawn, by the training which they undergo within the organization itself, by the discussion and debate which shapes the interpretative community in which they operate, and ultimately by the way in which their decisions are reviewed by their colleagues informally and their superiors formally (Piore 2008).

DARPA is widely understood to embody a series of unique tacit rules implemented at the "street level" by its program managers, that reflect the organizing principles of its culture, and these are not typical of similar such rules at other R&D agencies. The DARPA ruleset includes[7]:

- a flat, non-hierarchical organization, with empowered program managers,
- a challenge-based "right-left" research model,
- emphasis on selecting highly talented, entrepreneurial program managers (PMs) who serve for limited (3–5 year) duration
- research is performed entirely by outside performers, with no internal research laboratory

[6] Discussion by Kaigham Gabriel, DARPA Deputy Director, at forum on Leveraging DOD's Energy Innovation Capacity, at the Bipartisan Policy Center, Washington, DC, May 25, 2011.

[7] See, for greater detail on these features, Van Atta (2008) and Bonvillian (2009a).

- projects focus on a "high-risk/high payoff" motif, selected and evaluated on what impact they could make on achieving a demanding capability or challenge
- initial short-term funding for seed efforts that scale to significant funding for promising concepts, but with clear willingness to terminate non-performing projects

These rules are widely understood and have been previously explored in various studies. However, we believe these are not the only rules that need to be understood about DARPA and its culture.

2.2 Other important elements in the DARPA model

The model goes beyond the above well-understood features—historically, it has embodied a number of other deep features that should be accounted for. Within the overall context of its organizing framework DARPA's structure and focus has ebbed and flowed. In fact, its ability to flexibly adapt to changing circumstances is one aspect of its success: it has generally avoided becoming entrenched in particular technology pursuits, problem focus areas or organizational approaches and structures. Thus, as a living institutional organism there have been aspects of its management and implementation that have not necessarily been enduring attributes for all of DARPA's history, but are notable as contributing to its success. A discussion of these additional DARPA features follows below.

2.2.1 Multigenerational technology thrusts

DARPA does more than undertake individual projects. It has in many instances worked over an extended period to create enduring technology "motifs"—ongoing thrusts that have changed the technology landscape. Some of the notable examples of this are DARPA's work in information technology (IT), stealth, and stand-off precision strike. Some of these foci are what might be termed broad technology stewardship over a family of emergent technologies—including new sensing systems, such as infrared sensing, or new electronics devices (Van Atta et al. 1991a, III, IV-1–IV-5). In these thrust areas DARPA has been able to undertake *multigenerational* technology thrusts and advances over extended periods to foster multiple generations of technology.

The DARPA IT thrust area is the most notable in the context of ARPA-E's model. The IT thrust began with the now well-known vision of the first director of the Information Processing Technologies Office (originally prosaically labeled the Information Processing Techniques Office), J.C.R. Licklider.[8] It has endured over decades as "the ambitious vision of Licklider for revolutionizing information processing and applying to problems of 'human cognition' are being progressively realized" (Van Atta et al. 1991a, IV-7). It was sustained through ongoing collaborations and connections between successive PMs and office directors. Importantly, the information technology thrust was implemented largely outside of the Department of Defense through universities and small start-up firms that emerged from this research. As will be discussed below, these start-up enterprises were nurtured by the DARPA program through research grants and importantly through early purchase of their products as inputs into other DARPA and DOD programs.

The long-term support of a thrust area is neither a given nor an endowment at DARPA. The thrusts are defined generally as challenges appropriate to potentially needed

[8] Waldrop (2001) provides detailed illumination of Licklider's role in fostering the revolution in information technology which has been duly recognized as one of DARPA's most remarkable and compelling accomplishments. He also describes how Licklider's IPTO successors sustained it.

"breakthrough" capabilities. In some cases, as with high-energy particle beams, a thrust might be pursued for more than a decade, and then be terminated due to its lack of progress or impracticality. However, in the case of particle-beam weapons, the program re-emerged during the 1980s in conjunction with the Strategic Defense Initiative (Van Atta et al. 1991a, IV-9–IV-10). The basis of the thrust lay in its promise as a possibly revolutionary technology with the prospect of a transformational impact and evidence of its progress. The information technology thrust clearly demonstrated both this impact and this progress. The particle beam thrust, on the other hand, was terminated when it was unable to overcome increasing issues of technical complexity relative to performance, especially in conjunction with mounting costs.

It should be noted that persistence in an area is not universal in DARPA's ethos or history. DARPA was founded, as noted, as a projects agency—not a technology thrust agency. However, implicit in its organizational structure of program offices is (at least at specific times) a set of basic technical-implementation themes. The specificity and focus of these themes has changed substantially over DARPA's history. Moreover, there have been program offices with very dispersed and unrelated projects that sometimes raise the issue whether there is adequate coherence or focus. So it must be understood that only some of DARPA's research, and only some of the time, can be identified as an ongoing thrust. Other parts of the agency even at the same time may be pursuing a very eclectic set of individual projects that at least at that time appear to be disconnected. DARPA, then, remains a predominantly project-oriented office, except when it needs to periodically launch a new technology thrust.

From a lessons-learned perspective, in relationship to ARPA-E, it is worth noting that DARPA itself began with a set of explicit, but very high-level programmatic themes, termed "Presidentials": issues of space; missile defense; and nuclear test detection that met Presidential priorities. Although the first—"space"—was quickly transferred to the newly created National Aeronautics and Space Administration—NASA, the others galvanized a set of research programs aimed at a broad objective.[9] Given their high level imprimatur, these programs were sustained over many years, as they addressed key, daunting challenges. Notably, it took senior DOD management (John Foster, Director of Defense Research and Engineering) to terminate DARPA's early missile defense work and get it transitioned to the Army. The result was that under his mandate the DEFENDER program for ballistic missile defense was transferred to the Army for implementation—including the transfer of staff from the DARPA program to the Army. This represented an early attempt to confirm DARPA's role as a technology development organization, not as a technology implementer.[10]

A crucial management issue at DARPA, therefore, is how to keep such thrusts, themes, or foci from becoming entrenched resource allocations that weigh down the organization at the expense of innovation. DARPA has not been immune from this phenomenon. Iteratively, it has taken high-level intervention from the agency director and above DARPA to overcome this tendency—and this at times has caused rancor. A more recent instance of this management issue was the controversy over DARPA's substantial reduction in funding for

[9] Licklider's IPTO Office initiatives in computing gathered momentum when Kennedy and McNamara concluded they had a major "command and control" problem from their experience in the Cuban missile crisis; expanding Licklider's program was the DARPA response (Waldrop 2001, 200–203).

[10] For DEFENDER transition to the Army, see Van Atta et al. (1991b, 1–17, 1–26). Interesting as a contrast, DARPA's initial assignment for detecting Soviet nuclear tests, the VELA program, remained within DARPA for many years, and the operation of the Large Aperture Seismic Arrays remained under DARPA for decades, as no appropriate agency could be identified to take on the responsibility (Reed et al. 1990, I-13–14).

university computer science programs under Director Anthony Tether in the 2003–2008 timeframe. While leaders in the computer science programs at universities protested this as undermining DARPA's noted successes in this field and cutting DARPA off from access to ensuing IT talent generations, Tether argued that in his view the research in question was not high enough on the high-risk/high-payoff metric to be appropriate for DARPA (Bonvillian 2009a, 225–233). This is evidence of the strong tensions that can emerge between those who have received funding for a successful thrust over the years and the agency's management that has to make choices on what to fund. To keep such overarching thrusts dynamic as opposed to institutionalized is a major ongoing management challenge for DARPA leadership. The ability of researchers and the their supporters within universities, industry research labs and in Congress to press these interests should not be underestimated.

2.2.2 Complementary strategic technologies

DARPA has repeatedly launched related technologies that complement each other, which help build support for the commercialization or implementation of each. This concept of complementary technologies also ties to the notion of program thrusts.

One way of thinking about this category is that DARPA is not in the "thing" business, it is in the problem-solving business. While a specific innovation may have a major impact, it is unlikely that one such project by itself will adequately address a major challenge or problem. While DARPA may support an individual invention, it usually does so because that invention may be an element of an overall solution to a challenge. From an historical perspective, DARPA has almost never started out with a coherent program thrust (the exception being its inaugural Presidential issues, which were really more articulated overarching challenges than technical thrusts). The usual history is that a DARPA Program Office will pursue several disparate concepts initially and then, as the concepts shake out and begin to show promise, those that emerge will begin to cohere, and opportunities to integrate and link their developments will be identified. Also, as a program becomes better defined it becomes clearer what is missing in the ability to bring it into fruition, and thus, more targeted technology programs can be formed to seek alternatives to these barriers. This approach was certainly evident in DARPA's information technology programs as well as its microelectronics research. The key, then, to such developments is that they do not start out explicitly as coherent, multi-stage inter-linked development programs. Rather, they become this as merited and determined by the progress of the unfolding research.

One example of this inter-linking or complementarity is DARPA's funding of the development of computer workstations for integrated circuit design. DARPA program managers realized that the complexity of the designs that they were seeking in computer chips was outstripping the CAD tools that then existed and they therefore funded the development of advanced inter-netted design capabilities at various universities. Two results of this project were the SUN Microsystems and the Silicon Graphics workstations, both of which were developed out of Stanford University. As these capabilities became demonstrated, DARPA then urged their commercialization, but also supported their researchers doing novel chip design to acquire these systems. Notably, the resulting more advanced chips became available to developers of more powerful workstations, internet servers and routers and PCs, thus fostering a virtuous cycle of technology development and adoption.[11]

[11] See Van Atta et al. (1991b), Chapter XVII, "VLSI: Enabling Technologies for Advanced Computing," for discussion of this approach, especially Annex B to this chapter on the SUN Workstation.

The management lesson here is that such complementarity is not predetermined nor necessarily obvious at the outset. However, if the research is defined too narrowly and without some overarching integrated perspective (such as a thrust) it is less likely that, as the projects emerge, with some succeeding and others not, that the linkages and complementarities amongst them will be identified. To reiterate, the purpose of the research efforts is not "things" per se, but to solve overarching and daunting challenges or problems (Van Atta et al. 2003b, S-12–S-13). The evolving efforts to do that then help define the synergies and linkages as the projects evolve, with resulting complementary technologies.

2.2.3 Confluence with an advocate community

DARPA has spawned new economic sectors, enabling new firms which have garnered venture capital (VC) support. Accordingly, DARPA has been able to make its advances reinforce each other—it has been able to play an intermediary role with industry in part by building an advocate community across sectoral lines. How has it accomplished this?

Since DARPA itself does not implement the results of the research it sponsors, its main path to effecting implementation is by fostering and supporting the community of what we can term "change-state advocates" as a convener and instigator. In many fields initiated by DARPA research, the initial extant research capabilities are disparate and dispersed. Since the field is new, it is not well supported within the university science community and since it only has, at best, nascent technology to demonstrate, there is little in the way of investor or industry support. Thus, a key element of DARPA's success in such areas as information technology, sensor systems, advanced materials, and directed energy systems is building the community of change agents—a broad community fostered over time from its program managers, from "graduates" of the DARPA program who go on to roles in academia and industry, and from contractors in universities and industry trained in the DARPA model and technology approaches. Importantly, this creates a close-knit network of individuals who know and trust each other, breaking down information/collaboration barriers. This community confluence, in turn, creates a connection with the private sector and its ability to spur implementation.

A former DARPA Office Director explains one way this community builds itself:

> Good DARPA PMs create the conditions for their individual contractors to cohere into a technical community. The most visible way is through regular (usually annual) program reviews at which all contractors present their work—and where the really good conversations take place in the hallways as participants start seeing how they can connect and further their work. This isn't forced by the PM but s/he plays a vital role in nurturing the process. I got to participate in this in semiconductor process technology and a couple of other areas, but there are dozens of examples of technology communities that started this way. I see ARPA-E doing the same.[12]

A corollary to this community development, then, is that it fosters DARPA's role as an intermediary between companies to get them to consider working together in value-add ways against their own near-term individual interests. Companies developing new ideas generally value their intellectual property and proprietary position over the value of collaboration. The Federal government R&D agencies, and DARPA in particular, however, tend to have a more detached "50,000 foot" view of the innovation landscape and despite

[12] Communication from Arati Prabhakar, former DARPA PM and Office Director, and later Director of NIST, May 27, 2011.

industry's tendencies, DARPA uses this community confluence to incentivize high value collaborations without violating the confidentiality of what they learn from industry behind closed doors.

2.2.4 Connected to larger innovation elements

Going beyond the confluence with its support community, DARPA has been an actor within larger innovation efforts—where it is often instrumental, but seldom a sole actor. This is important to DARPA's effectiveness because it does not have its own research facilities and its program managers do not perform their own research. Thus, DARPA PMs' most important function is to identify and support those who have the potentially disruptive, change-state ideas and will ably perform the research. Thus, the PM is an opportunity creator and idea harvester within an emerging technology field. From this concept-idea scouting perspective DARPA has spawned groups of researchers, and from that, new firms that act to help effectuate the program's overall vision.

The information technology thrust initiated by J.C.R. Licklider is the most notable example of DARPA creating a dynamic iterative innovation eco-system, based on university programs and start up enterprises. The major initial research centers for this evolving and expanding nexus of technologies included MIT (with Project MAC), Carnegie-Mellon, Stanford, Berkeley, UCLA, USC (with ISI), and CalTech. However, early-on entrepreneurial private firms, such as Bolt, Beranek and Newman (BB&N), DARPA's internet contractor, also played key roles (Reed et al. 1990, Chapter XX, "ARPANET").

In the IT sector, DARPA followed a conscious "dual use" approach, recognizing that IT (unlike, say, stealth) would be relevant to civilian as well as military sectors, and that by spinning technologies into civilian sectors which could focus more capital than defense procurement on development and applications, military IT needs could leverage off civilian development and the resulting wealth of applications. Its connections to larger innovation elements enabled DARPA and DOD many more fronts of technology advance than defense development alone could have evolved. Since US Cold War success arguably derived from its IT advantage and the "Revolution in Military Affairs" it enabled, "dual use" was a profoundly advantageous leveraging success.

Thus, the emerging technical opportunities from the DARPA IT programs had synergistic effects with the high-tech investment communities in IT springing up principally in the San Francisco and Boston areas around Stanford, Berkeley and MIT. While initially early DARPA director Robert Sproull felt that computer developments should be left to the dominant firm in the market, IBM, Licklider convinced him that IBM was mainly interested in large-scale batch processing applications and not interested in the technology for the new concepts of time-sharing and individualized computing that Licklider was championing (Reed et al. 1990, Chapter XIX). Thus, DARPA fostered research at these key universities, initially at MIT, and this helped such firms as Digital Equipment (DEC) expand footholds in a domain that was dominated by IBM's presence. From DARPA-funded IT research starting in the 1960s can be traced an expanding number of firms and commercial applications from DEC to TELENET (the original internet ISP), Xerox's Ethernet, Apple's desktop computing (following leads from Xerox Parc), CISCO Systems (internet protocol routers), SUN Microsystems, Silicon Graphics, MIPS, Thinking Machines, Mentor Graphics, Vitesse Semiconductor, and TriQuint Semiconductor.[13] From these firms second and third order spin-offs and derivative firms can be identified, such as

[13] See, for example, Fong (2001) and National Research Council (1999).

Juniper systems, UUNET, and eventually even Google and Facebook, that built their businesses on the underlying technologies and capabilities, as well as the investment structure of the earlier firms (for example, Anders Bechtolsheim of SUN was one of the ground floor investors in Google).

Moreover, DARPA programs, such as the VLSI program in advanced microelectronics, had impact by providing underlying technologies that not only spurred new companies, but also raised the competency and capabilities across the entire industry. The support of the VLSI design, production, and higher level computer architecture and design was both infrastructural—such as the MOSIS program and the support of VLSI design courses at universities—and technological, supporting new integrated circuit design concepts of Carver Mead and Lynn Conway, that had cross industry impact on major incumbent firms, such as Intel, as well as start up firms, such as MIPS (Van Atta et al. 1991b, Chapter XVII).

The impact of DARPA pressing innovation onto existing firms, while difficult to assess, is exemplified by the following comment by a noted venture capitalist:

> If DARPA had not been available, university researchers would have had to use 'free' equipment from companies like Digital and IBM to do their research. DARPA funding of research was essential in providing an ability to make independent choices.[14]

In addition to connecting with companies, venture capital firms (VCs) played a crucial role in the commercialization of DARPA's information technologies. Many of the most prominent California VCs[15] literally grew up with DARPA, with DARPA-based technologies playing a key role in their success and creating deep synergy between these two innovation elements. There are numerous very specific examples, including Vinod Khosla and SUN Microsystems, FED Corp in displays and Silicon Graphics. VCs also followed DARPA programs as a basis for identifying the "next big thing;" because of the dynamism of the research award process, DARPA awards tended to give their small and start-up firms a "halo effect," effectively marking them for follow-up support by VCs. VCs and DARPA became symbiotic in the IT sector and more broadly, operating as mutual enablers.

However, this connection process with industry has not always worked; DARPA has had difficulty in staging its technologies for entry into industries at times. For example, DARPA's "High Definition Display" program focused on creating capabilities in the emerging Flat Panel Display technology was not able to successfully intercept Japan's lead in commercializing this technology. Other examples of unsuccessful endeavors include DARPA's investments in the Thinking Machine development of the Connection Machine parallel processing computer and efforts to commercialize digital gallium arsenide computer chips. These less successful endeavors point to the facts that:

(1) DARPA is a proof-of-concept technology agency, focused on high-risk disruptive capabilities—success in such efforts is not guaranteed;
(2) There are crucial factors beyond technology development and demonstration that impinge on success.

However, this downward and outward linking into the research community and commercial industry is only one aspect of DARPA's connectivity larger innovation elements. DARPA, as an agency of the Department of Defense, is part of a broader innovation structure within and for DOD. Crucial here is that DARPA is an independent organization

[14] Interview with Vinod Khosla (Van Atta et al. 1991b, 17-B-11).

[15] See Gupta (2000, 1–11) for discussion of the technology innovation orientation of west coast VCs.

under the Secretary of Defense and is explicitly separate from the military service acquisition system. While the Secretary of Defense and the underlying Office of the Secretary of Defense (OSD) bureaucracy rarely directly involve themselves in DARPA's individual research programs, OSD leadership elements at various times have played a strong role in identifying the mission challenges upon which they want DARPA to focus (see further discussion below on "Ties to Leadership"). Whether the challenge is "get us into space," "offset the Soviet advantage in numbers and mass," or "overcome terrorist abilities to strike within the US," OSD leadership has periodically turned to DARPA with broad but explicit mission charters unique from those of the existing military research structure. In addition, and relevant here, DARPA, working with OSD, has been able to tie its advances to the larger innovation elements in DOD, often implementing its technologies through service procurement programs.

To summarize, DARPA has been an actor and creator within larger innovation systems that include emerging industry sectors, the venture support that backs them, and entities within DOD itself.

2.2.5 Takes on incumbents

DARPA at times has invaded the territory occupied by powerful companies or bureaucracies. As discussed above it drove the desktop personal computing and the internet model against the IBM mainframe model. On the military side of the ledger, cooperating with others in DOD, it drove stealth, unmanned systems, precision strike and night vision capabilities, despite the lack of interest and even express objections of the military services. At times this has taken special mechanisms beyond or outside of (but in coordination with) DARPA to achieve.

For example, the Advanced Concepts Technology Demonstrator (ACTD) program was created in 1993 by OSD Deputy Undersecretary for Advanced Technology Larry Lynn (later DARPA Director from 1995 to 1998) to move unmanned high altitude, long endurance unmanned air vehicles (UAVs) into initial use. This was used to get the Predator and the later Global Hawk systems into the hands of combat units when the military services would not further their development after DARPA completed its proof-of-concept developments.

Thus, DARPA, at critical technology junctures, has not been afraid of push-back against powerful incumbents, both leading industry firms and the military, to press disruptive technologies forward.

2.2.6 First adopter/initial market creation role

In addition to ties to demonstration capabilities, DARPA also has undertaken a technology insertion or adoption role. In coordination with other parts of DOD has been able to create initial or first markets for its new technologies. DARPA and DOD were first adopters of many of the IT advances DARPA supported—e.g., work stations (SUN, Silicon Graphics), and ARPANET as MILNET.

> DARPA then provided a critical assist to the launching of Sun by extending funds to a number of academic institutions to permit them to acquire workstations for their own institutional users and networks. According to Khosla, academic institutions (particularly the University of California at Berkeley, Stanford, and Carnegie-Mellon) accounted for roughly 80 percent of the orders received by Sun in

its first year of business, thanks to this DARPA funding (Van Atta et al. 1991, 17-B-8).

DARPA has relied, as discussed above, on both its confluence with its advocacy community, and its ties to larger innovation system elements, to achieve this.

2.2.7 Ties to leadership

DARPA has been particularly effective when it is tied to senior leaders that can effectuate its technologies through DOD or elsewhere. Just as Vannevar Bush and Alfred Loomis in World War II were able to press developing defense technologies into implementation using their direct links to President Roosevelt and Secretary of War Stimson, DARPA at critical technical moments has been able to call on senior allies. Several examples follow below:

- Undersecretary for Defense Research and Engineering William Perry—supported stealth and precision strike, as initiated and backed under Secretary of Defense Harold Brown. Initial interest in what became stealth technologies was driven by OSD seeking capability to overcome Soviet air defenses. Precision strike was driven by the Brown/ Perry desire to develop technological "offsets" to Soviet advantages in mass force, building on earlier DOD-DARPA efforts driven by the previous director for R&E, Malcolm Currie.
- Director of Defense Research and Engineering John Foster—a strong supporter for DARPA's night vision program and spearheaded DARPA's initial involvement in UAVs.
- DARPA Director of the Tactical Technologies Office Kent Kresa went to industry (Northrop) to head an Advanced Technology Division where he focused on bringing precision strike and stealth to fruition. Subsequently Kresa became CEO of Northrop–Grumman.

Because DARPA operates at the front end of the innovation process, it historically has required ties to senior DOD leaders to align with the follow-on back end of the innovation system.

2.2.8 Doesn't necessarily launch into a free market

DARPA embodies what is termed "connected R&D;"[16] it is not throwing its prototype technologies over the monastery wall, using a theory of "benign neglect" in the face of markets. It often uses DOD procurement to further its advances, and it funds, as discussed above, creative companies that can attempt to commercialize its products—it tries to guide its successful developments into commercialization, and builds portfolios of technologies to build depth for a technology thrust in emerging markets. *It is in the opportunity creation business*, in some cases picking technology "winners." In DARPA's exploration of radical innovations it is generally recognized that its developments are ahead of the market—the research it is fostering does not meet an existing market need, but instead is creating a capability—a new functionality[17]—that may (if successful) create a new market or application.

[16] See discussion of this term in Bonvillian (2009a, 206–210).

[17] See discussion of this functionality concept in Weiss and Bonvillian (2009, 185–190).

A military example of this dynamic of technology push rather than demand pull is DARPA's sponsorship of high altitude, long endurance UAVs, which created new capabilities for which, at the time, there were no service "requirements." In fact, when these systems, such as the Predator and later Global Hawk, were first demonstrated, the military services actively delayed and discouraged their transition and development. Similarly, DARPA's fostering of internetted personal computing was ahead of any market foreseen by the incumbent computer firms, such as IBM and later, DEC. In developing such unanticipated new capabilities it is unlikely that current market mechanisms and especially current firms meeting those existing markets will be the primary means to bring the capabilities to fruition. From a DARPA standpoint the question is how and in what manner should it foster the transition—and for how long. As the opportunity creator DARPA has in many instances developed a new capability up to a technology demonstration and then found that the potential recipients—either in the military or commercial environments—are not ready or interested to take them further. Several times DARPA has essentially backed off further support and other times it has supported additional research that it sees as overcoming the risks that impede the technology's transitioning. However, there is a well understood rule that DARPA itself is not in the business of transitioning—it is in the business of inventing.

In summary, DARPA doesn't just throw its technologies out into the world and pray that markets will pick them up, it uses its ties to defense procurement and to emerging companies to try to align its technologies with institutions in the difficult back end implementation stage.

Even when it is focused on "connected R&D" and a specific technology, it should be noted, however, that DARPA is "all about competition" amongst ideas and has multiple mechanisms to identify, assess and evaluate alternatives and options, and will restructure or terminate ideas that are judged to not be panning out—especially those that appear not to be making a big enough difference relative to the status quo. This does raise an important question: who decides? At DARPA, as well as other research organizations, individuals often have trouble "letting go" of their vision, even when it isn't working. DARPA's main decision focus is the program manager, but the Office Directors and the Director play important roles in reviewing progress and assuring that programs are scrutinized. Since a PM typically only has 3–5 years on station to "make something happen," he or she has an incentive to make choices based on what projects appear to have the best chance of success. Just recently, DARPA's F-6 "Distributed Satellite" program was totally restructured with the initial contractor's program halted, when the new program manager decided that the effort was not likely to achieve the objectives.

2.2.9 Ahead of the game

There is one additional aspect that should be noted, since DARPA is a government agency. While there is a history of Congress pressing a recalcitrant military to implement innovations, such as aviation and the aircraft carrier, Congress has also at times played the opposite role, interfering in technology advances. DARPA historically, has tried to stay ahead of Congressional interference and micro-management by developing coherent narratives about its technology approaches that show DARPA's projects to be "ahead of the game." It has worked to avoid a situation where Congress has captured the narrative and forced DARPA involvement. As a result, DARPA has been almost "earmark" free.

2.3 Problems in tech paradise

It should be noted as a caveat that the above discussion is of DARPA on a good day; it has bad days, as well. There have been periodic problems at DARPA. It is in the end a human institution, and these concerns provide further lessons. It also faces challenges from **new realities**. The globalization of US industry has created challenges for an agency charged with technology leadership to avoid technology surprise (Bonvillian 2009b, 72–75). DARPA, for example, is only now working on a multi-element strategy to adequately respond the global erosion of the US manufacturing capabilities and depth which will affect the abilities of the US to field advance technologies.[18] With the imminent tightening of defense budgets DARPA will face also increased challenges on how to use military procurement to create initial markets to transition its technologies.

In recent years, as briefly cited above, DARPA defunded a significant part of its university research base for advanced IT research, in turn affecting the strength of the DARPA IT technology community and the flow of outstanding university IT talent into DARPA (Bonvillian 2009a, 225–233), although the current leadership is attempting to improve this situation. For example, **strong office directors** with extended experience aiding talented PMs with less DARPA and DOD experience, have often been key to DARPA, providing in-depth technology management and leadership for shorter-term and usually less-experienced PM's. However, it appears that in recent years this strong officer director model has been cut back in favor of a strong director; while current DARPA leadership has been working to restore this position's authority, it is not an easy task. The strong director approach also affected the ability of its PMs to act as advocates for their technologies—as vision enablers—a traditional key PM role important to DARPA's capabilities. The strong director with a strategic approach may at times run contrary to DARPA's tradition of "hire smart PMs and empower them."

Another problem has been the **hand-off between program managers**. Demand pull from military procurement has helped keep DARPA work moving somewhat smoothly during transitions from one program manager to another. Even so, shifts in DARPA PM management sometimes become "disruptive" themselves, in an undesirable way. For example, these problems have affected DARPA's Strategic Computing program and recently the Ultra High Performance Computing Program, where program continuation has not been smooth.

If military demand pull is weak—as it certainly sometimes has been when DARPA was out ahead of the technology compared to the services (for example, with the arsenal ship and UAVs)—the DARPA model can suffer from too many stops, starts, and changes in direction. These can be the result not of careful reassessment of the technological frontiers and where the work should be going, but some combination of true belief and whimsy on the part of DARPA management. **New leaders** often have an instinct to make big changes even if operations are optimal so that they can "leave their mark." When this occasionally happens at DARPA, there can be a real issue whether the culture can supersede such occasionally disruptive leadership, although its history as a highly flexible, small and intimate program, with fewer bureaucratic controls than more traditional R&D programs, helps it.[19] Thus, what has been an overall DARPA strength—talented directors—can at times be a weakness.

[18] DARPA is working to build a manufacturing technology portfolio; see summary of some of these elements in MIT Washington Office (2010, 4–6.), See, generally, Tassey (2010) and Pisano and Shih (2009).

[19] Some observers counter that DARPA's productivity generally has remained high, despite such concerns. See Fuchs (2011).

There is another issue area, too, that requires notice: the **transition to implementation**. DARPA has worked hard to make this work, as discussed in many of the points above. But as a radical innovation organization, inevitably it is only secondarily concerned with transitioning the results into implementation. Some have accused DARPA in the past of too often being a "hobby shop" for talented PMs. Sometimes this transition capability has been DARPA's greatest strength and sometimes its biggest weakness. It has been noted that, "if fielded disruptive capabilities are the objective, it will be insufficient to generate an example … [such as a proof-of-principle prototype]… and then rely upon the traditional DoD/Service acquisition system to recognize its value and implement it" (Van Atta et al. 2003b, 64). This problem will be further explored in detail in Part 4, below.

In conclusion, the above discussion of DARPA cited the well-known elements of its innovation culture, and focused on a number of less well-understood elements that have been important to its strength and capabilities. Both offer lessons in the energy technology sector to ARPA-E, which will be explored below. In addition, DARPA, like any human-created and run organization, is not perfect and a number of problems it has faced offer lessons in addressing how to best organize and manage ARPA-E.

3 ARPA-E: A new R&D model for the department of energy

3.1 Replicating basic DARPA elements

ARPA-E[20] was consciously designed by Congress to apply the DARPA model to the new energy technology sector.[21] Currently funded at $180m for FY2011, it is about the size of a DARPA program office. It has emphasized speed—rapidly moving research breakthroughs into technologies, through a process it labels "Envision-Engage-Evaluate-Establish-Execute."

With $400 million received in the 2009 stimulus legislation cited above, it has awarded funding in six energy technology areas through spring 2011, which are briefly summarized

[20] The following discussion on ARPA-E derives from ongoing discussions since ARPA-E's initial formation between author Bonvillian and ARPA-E's director, its deputy director for operations, and one of its program managers; author Van Atta had similar discussions with ARPA-E officials during this period. Both authors had an extended discussion session with four ARPA-E program managers about the ARPA-E model on April 5, 2011, which was particularly helpful in developing this paper. Both authors have long been observers of the ARPA-E formulation process; both testified before the House Science and Technology Committee on the ARPA-E authorizing legislation, HR-364 (2007), Bonvillian (2007b), Van Atta (2007). Author Bonvillian, in addition, wrote about the proposal (Bonvillian 2006) and (together with former DARPA Deputy Director Jane Alexander and former DARPA General Counsel Richard L. Dunn) reviewed ARPA-E concepts for Department of Energy Chief Financial Officer (CFO) Steven Isakowitz and his office, over several weeks in February and March 2009, as the CFO's office led the DOE effort to form and stand up ARPA-E within DOE.

[21] See, H.R. 364 (2007), America COMPETES Act (2007). See, also, America COMPETES Act Reauthorization 2010, Sec. 904, amending section 5012, and House Committee on Science and Technology Hearings on ARPA-E concept (March 9, 2006; April 26, 2006). The conceptual origin for ARPA-E as a DARPA model for energy stems from the National Academies' report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (National Academies 2007, 152–158). For a discussion of some of the issues under consideration in the initial Congressional design of ARPA-E, see Bonvillian (2007a). For an early description of ARPA-E's mission and role from its first director, see Majumdar (2009).

below.[22] These follow a "challenge-based, focused-program" approach modeled on DARPA (this was formed after an initial wide open "early harvest" funding opportunity noted below).

- The "Innovative Materials and Processes for Advanced Carbon Capture Technologies" program (IMPACCT) aims to develop technologies to capture 90% of CO2 from coal power plants at much higher efficiency and lower cost; research approaches include advanced new technologies for capturing and converting CO2 at power plants through a range of approaches, from catalysis to membrane sorption.
- ARPA-E's "Electrofuels" initiative aims to synthesize biofuels using micro-organisms to convert CO2 and water into liquid fuels, seeking a ten fold increase in efficiency over current biofuel production processes.
- The "Batteries for Electrical Energy Storage in Transportation" program (BEEST) seeks ultra high-density, low cost battery technologies for long range, plug-in electric vehicles, aiming at doubling vehicle ranges and enabling a four fold reduction in costs from current battery technologies. Technology approaches extend from advanced lithium–ion concepts to over-the-horizon new battery concepts like lithium-air batteries and an "all-electron battery".
- The "Agile Delivery of Electrical Power Technology" program (ADEPT) seeks to develop materials for advances in magnetics, switches and, high-density storage to improve the efficiency of power electronics to reduce electricity consumption by up to 30%. This is an area where the U.S. lead in advanced materials such as SiC and GaN-on-Si could serve as platforms for success in next generation (beyond Si-based) power electronics.
- ARPA-E's "Grid Scale Rampable Intermittent Dispatchable Storage" program (GRIDS) proposes to develop new technologies that create widespread cost-effective grid-scale storage, helping to balance renewables and power supply fluctuations with demand. The program is aiming for new storage systems with efficiency and cost comparable to pumped-hydro. Because the energy storage R&D/technology community has traditionally focused on energy density, new constraints largely on the cost side have brought out numerous new ideas.
- The "Building Energy Efficiency Through Innovative Thermodevices" program (BEETIT) seeks to develop cooling technologies for new and retrofitted buildings to significantly increase energy efficiency. The program has goals to increase air conditioning efficiency by 50% and sharply cut refrigerant global warming impacts.

ARPA-E includes two DARPA veterans among its eight PMs, one a former DARPA PM, the other an experienced DARPA performer and advisor. Consistent with its legislative history, it has worked to replicate the DARPA approach. The discussion below lists well-known elements in the DARPA ruleset and reviews how ARPA-E reflects and has adapted that model.

ARPA-E is a ***flat, non-hierarchical*** organization, effectively with only two levels—eight program managers (PMs) and its director,[23] Arun Majumdar, formerly a Berkeley

[22] The six ARPA-E program directions awarded to date listed here can be found at ARPA-E 2010. A further award offering was announced by Secretary Chu on April 20, 2011 for rare earths, biofuels, thermal storage, grid controls, and solar power electronics (Department of Energy 2011b).

[23] ARPA-E also has a PM who is deputy director for technology, and several additional teams: an "operations" group supervising its contracting process, including a counsel (who implements ARPA-E's unique personnel and contracting authority despite the very different procedures of DOE's management bureaucracy) and deputy director for operations; a commercialization team (discussed below); and a group

professor with senior administrative experience in DOE's Lawrence Berkeley Lab who has also worked on forming companies.[24] Like DARPA, the ***program managers are "empowered,"*** each with strong authority and discretion to administer a portfolio of projects in a related energy field, from storage to biofuels to carbon capture and sequestration. Like DARPA, the ***project approval process is streamlined***—the PMs evaluate and conceive of the research directions for their portfolios, then go through a critique of that approach with the director (and discussions with colleagues); they go through a similar discussion process over proposed contract awards. Essentially, there is only one approval box to check—the director—who retains approval authority before the contract is awarded, which generally goes very quickly. ARPA-E emulates DARPA's reputation for fleet-footed decision-making. Like DARPA, ARPA-E is not bound by the traditional research selection processes, such as peer review or hierarchical bureaucratic lines of authority. It operates through a strong PM selection process outside of peer review. Although ARPA-E uses strong expert reviews to guide PM decisions, there is no "peer review" where outside researcher peers make the actual final decisions on what gets funded. As at DARPA, this PM selection process generally avoids the conservatism and caution that often afflicts peer review, which tends to reject higher risk research awards if there are more than four applicants per grant award.

Like DARPA, the PMs use a ***"right-left" research model***—they contemplate the technology breakthroughs they seek to have emerge from the right end of the pipeline, then go back to the left side of the pipeline to look for proposals for the breakthrough research that will get them there. In other words, like DARPA, ARPA-E uses a ***challenge-based*** research model—it seeks research advances that will meet significant technology challenges. Like DARPA, ARPA-E tends to look for ***revolutionary breakthroughs*** that could be transformative of a sector—thus far, it has had a penchant for high-risk but potentially high-reward projects. ARPA-E's design is metrics-driven and "challenge-based" for funding opportunities. Metrics are defined in terms of what will be required for cost-effective market adoption in the energy industry. PMs propose to the research community what will be required in terms of technology cost and performance for adoption and then ask this community to pursue this with transformative new ideas.[25]

Like DARPA, ARPA-E's PMs are a highly-respected, technically talented group,[26] carefully selected by a director who has asserted that there is no substitute for ***world-class***

Footnote 23 continued
of fellows (typically outstanding recent university PhDs, who support the PMs, discussed below). But the R&D operating core of ARPA-E is very flat: its director and its group of PMs. Regarding this term, the original enabling statute uses "Project Managers", see, America COMPETES Act (2007), Sec. (f)(1)); the term "Program Directors" was substituted by America COMPETES Act Reauthorization (2010), Sec. 904(f)(1)(C)(i), which amended ARPA-E's enabling statute in 2010. ARPA-E Director Majumdar decided to use the term "Program Directors" to emphasize how empowered its portfolio managers are. However, the term Program Managers is used here to parallel the term used in DARPA because the functions are similar and it is a functional title which is widely understood in the technology community.

[24] ARPA-E Director Majumdar's bio available at Majumdar (2011).

[25] This approach was used in some specific programs at DARPA. One specific example was the Global Hawk HALE UAV, which had a "firm requirement" of a fly away cost of $10 million per unit. Importantly, while Global Hawk is generally viewed as having had a major impact on US military capabilities, this cost per unit was not met with the initial systems developed under DARPA and subsequently the Air Force has re-designed the Global Hawk to be a much larger and much costlier system (Van Atta et al. 2003b, 45–49). See, also, Porter et al. (2009, Vol. II, 49–50) on Global Hawk cost and schedule difficulties.

[26] ARPA-E (2011) PMs' bios available at: http://arpa-e.energy.gov/About/Team.aspx. The PM group includes a deputy director for technology.

talent. Typically, the PM's have ***experience in both academic research and in industry***, usually in start-ups, so they generally know from personal experience the journey from research to commercialization. Recognizing that the ability to hire strong talent quickly was a key DARPA enabler, the House Science and Technology Committee, which initiated the ARPA-E authorization, gave ARPA-E, like DARPA, the ability to supersede the glacial civil service hiring process and rigid pay categories. In fact, ARPA-E's broad ***waiver of civil service hiring authority***[27] may be without precedent in the federal government.

Like DARPA, ARPA-E's research program is organized around the 3–5 year lifetime of its PMs. By statute ARPA-E's PMs are limited to 3 years of service (although this can be extended),[28] so, as with DARPA, this means they must work to get their projects into prototype and implementation stages in the three or so years they are at ARPA-E. Thus, ***the project duration yardstick is the life of the PM***. This means that ARPA-E must forego much long-term research; it must build its project portfolio by seeking breakthroughs that can move to prototype in—for science—a relatively short period. It will aim, therefore, like DARPA, at ***innovation acceleration***—projects that can move from idea to prototype in the program life of its program managers. The House Science and Technology Committee, mirroring DARPA, also emphasized the availability to ARPA-E of highly flexible contracting authority, so-called "***other transactions authority***," which enables ARPA-E to emulate DARPA's ability to quickly transact research contracts outside of the slow-moving federal procurement system.[29] Although this authority has not yet been fully utilized, it remains promising as ARPA-E moves into new areas, such as prize authority, discussed below.

Like DARPA, ARPA-E is also instituting the ***"hybrid" model***, providing funding support for both academic researchers and small companies and the "skunk works" operations of larger corporate R&D shops. DARPA has often tied these diverse entities into the same challenge portfolio and worked to convene them together periodically for ongoing exchanges. This has tended to improve the handoff from research to development by combining entities from each space, easing technology transition. Like DARPA, ARPA-E has worked from an ***island/bridge model*** for connecting to its federal agency bureaucracy. For innovation entities in the business of setting up new technologies,[30] the best model historically has been to put them on a protected "island" free to experiment, and away from contending bureaucracies—away from "the suits" (Bennis and Biederman 1997, 206–207).

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[27] America COMPETES Act (2007), Sec. 5012(f)(2)(A), as amended by American COMPETES Act Reauthorization (2010), Sec. 904(g)(3)(2)(A)(i) (ARPA-E civil service waiver) In contrast, DARPA uses Intergovernmental Personnel Act (IPA) authority to hire PMs promptly (hiring can be completed in a day) from academia or industry, with the employee still paid through his or her former employer at the former salary level.

[28] America COMPETES Act (2007), Sec. 5012(f)(1)(C), as amended by American COMPETES Act Reauthorization (2010), Sec. 904(g)(2)(C).

[29] For DARPA's Other Transactions Authority (OTA), see, P.L. 101-189, 10 U.S.C. 2389 (enacted 1989); P.L. 103-160, Sec. 845. For a discussion of DARPA's OTA authority, see, Kaminski (1996), Dunn (1995, 1996a, b, 2007). The Department of Energy received "Other Transactions Authority" in the Energy Policy Act (2005), Sec. 1007. However, it was only utilized once (GAO 2008) until the advent of ARPA-E, when ARPA-E used it three times in 2009 in making its initial grant awards. See, America COMPETES Act Reauthorization Act (2010), House Comm. Rep. 111-478, of House Committee on Science and Technology, Subtitle B ("To attract non-traditional performers and negotiate intellectual property agreements ARPA-E also uses flexible contracting mechanisms called Technology Investment Agreements authorized for the Department as 'Other Transactions Authority' in the Energy Policy Act of 2005.").

[30] For analyses of private corporation and DOD defense S&T programs illustrating how successful radical innovation programs are constructed and managed in this manner, see Van Atta et al. (2003a).

ARPA-E, as it was set up within DOE, has required both isolation and protection from rival DOE R&D agencies and the notorious bureaucratic culture at DOE that may battle it for funding and the independence it requires. From the outset, therefore, it needed a bridge back to top DOE leadership to assure it a place in DOE's R&D sun—it received this from Energy Secretary Steven Chu, who was one of the original proponents of ARPA-E while serving on the National Academies' *Gathering Storm* report, and later testified in support of ARPA-E before the House Science and Technology Committee in 2007.[31] It helps, too, as cited above, that ARPA-E's first director was a trusted technical peer and colleague from Secretary Chu's Lawrence Berkeley National Lab days. On a day-to-day basis, DOE Chief Financial Officer Steven Isakowitz oversaw ARPA-E's initial stand-up in its embryonic days immediately after its Stimulus funding (ARRA 2009) was passed to bring ARPA-E to life, serving as an early godfather. Thus, ARPA-E had a critical bridge back to leaders who could protect its independence and funding. It was located by DOE's CFO one block from DOE's Forrestal building in Washington, on the floor of an adjacent non-DOE building—this gave it a handy bridge back to its DOE godparents, but assured that it would have its own island for its own team separated from the DOE bureaucracy.

Well aware of this evolving ruleset, Energy Secretary Chu has remarked—consistent with DARPA's history—that if just one in twenty ARPA-E projects is commercialized, the energy technology landscape could be transformed.[32]

3.2 New elements at ARPA-E

Thus far, we have described ARPA-E as though it was a clone of DARPA. However, ARPA-E faces a very different technology landscape than DARPA. DARPA has been able to launch its technologies into two territories that simplified its tasks. First, it has often been able to place its technologies into the procurement programs of the military services. In this approach, the military is able to serve as the testbed and initial "first" market for new technologies emerging from DARPA. As discussed above, this isn't automatic; it required creative work and senior allies, for example, for DARPA to persuade the military services to adopt stealth and UAV technologies. But when it works, it greatly eases technology transition. Second, as discussed at length above, DARPA also launches its technologies into civilian sectors—its keystone role in the IT sector is the most famous example; the internet, VLSI computing and desktop computing features are among the many noteworthy IT technologies it supported. However, the IT revolution DARPA nurtured was a technology frontier, an example of "open space" technology launch.[33]

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[31] Secretary Chu also personally selected ARPA-E's director, a Berkeley colleague and friend, who was his former deputy director at Lawrence Berkeley National Laboratory. This assured a very close connection between ARPA-E and the top agency leadership, somewhat comparable to such noteworthy technology "bridge" relationships as that between, for example, Radiation Lab founder Alfred Loomis and Secretary of War Henry Stimson, and Vannevar Bush, President Franklin Roosevelt's World War II science czar and Harry Hopkins, Roosevelt's chief personal aide. See Conant (2002, 178–289) on Loomis and Zachary (1999) on Bush.

[32] Secretary Chu, as noted above, has long been an ARPA-E proponent: see Chu (2006).

[33] As discussed in Part 2, the frontier was not entirely open; DARPA did take on the IBM mainframe model in supporting disruptive technologies to achieve personalized computing and the internet. But it also took on a set of technologies that were not of primary interest to IBM and in fact were of very low priority to it compared to its mainframe computing.

In contrast the energy sector that ARPA-E must launch into is occupied territory not open space—energy is already a complex, established, "legacy" sector (CELS) (Bonvillian and Weiss 2009). New energy technologies have to perform the technology equivalent of parachuting into the Normandy battlefield; there is already a technology-economic-political paradigm that dominates the energy beachhead that must be overcome. Because it faces a very different launch landscape than DARPA, ARPA-E is learning to vary its organizational model. In addition, ARPA-E has assembled what is by all accounts a talented team; they have put in place their own ideas on how to operate their new agency, as well. Thus, ARPA-E is not simply replicating DARPA, it is finding and adding its own elements appropriate to the complex energy sector where it concentrates and to its own staff. Some of these constitute new innovation lessons potentially applicable to other agencies and projects. A number of these new elements and variations from the DARPA model, as well as organizational features ARPA-E is focused on, are discussed below.

A. Sharpening the research visioning, selection, and support process

Every strong innovation organization, from research groups, to start-ups and firms, to federal research agencies, must build a strong innovation culture.[34] Organizational cultures in the innovation space tend to lock-in quite early in the organizational history, and, once set, patterns of interactions and performance tend to become engrained into the entity's culture. ARPA-E, led by its director and PMs, all of whom have had experience in a range of innovation organizational cultures, including DARPA, have worked to build their own innovation culture within ARPA-E. While it shares many features with DARPA, as noted above, it has its own areas of emphasis.

ARPA-E's director and PMs emphasize that they are working in what they call **"the white space" of technology opportunities**. Starting with their first research award offering,[35] they assert they have consciously attempted to fund higher risk projects that could be breakthroughs and transformational in energy areas where little work previously has been undertaken. This means that their research awards are purposely made seeking transformations, not incremental advance. Comparable to the DARPA model, this approach has placed **technology visioning** at the very front of the ARPA-E's research nurturing process (Carleton 2010).

[34] A working ruleset for optimal innovation organization cultures is set forth in, Bennis and Biederman (1997, 196–218). A number of these Bennis/Biederman "rules" are (as of 2011) painted on the walls near the DARPA Director's office in DARPA's building in Arlington, VA.

[35] This perspective evolved from ARPA-E's first award offering for $150m, issued on April 27, 2009, which was entirely open-ended, simply seeking innovative new ideas for energy technologies from academic energy researchers and firms. While the small ARPA-E staff—the organization was just being assembled—anticipated that they would receive only some 400 applications (assuming, as one ARPA-E official put it later, "Whoever heard of ARPA-E?"); instead, they received over 3,500 applications. See, Kosinski (2009, 8). Because it faced an overwhelming application volume, this forced ARPA-E to assemble a major review effort relying on scientists throughout DOE to assist (which aided in their subsequent DOE community building effort, discussed below). Because they had far too many quality applications for their limited initial award funding (they only made 37 initial awards), they developed their "white space only" approach described in the text above, which has since become a basic agency policy approach. Realizing that the energy tech sector was eager for a DARPA model in energy, and that there was already a major "tech buzz" around ARPA-E, the agency subsequently limited its award offerings to particular technology sectors, discussed above in the text in this section, to control the number of applications and make the review process manageable. However, to avoid disappointing and frustrating the initial wave of applicants, ARPA-E created its innovative energy technology "summit," described below. Thus, two of ARPA-E's more innovative approaches—"white space" and its now annual "summit" were lessons that came out of the near-nightmare of managing its first open-ended initial award process.

ARPA-E has implemented an interesting **two-stage selection process**, offering applicants a chance to offer feedback to the initial round of reviews. Because ARPA-E's director, like many researchers, had been personally frustrated by peer review processes where the reviewers in their responses to his proposals showed limited understanding of the science and technology advances behind his applications, he implemented a unique review process where his PMs allowed applicants to respond to their application reviews, followed by a further evaluation step. This "second shot" and "feedback loop" in the review process has improved evaluations because the PMs know their conclusions will be critiqued, has helped educate PMs in new technology developments, and resulted in a number of reconsiderations of applications, thus improving the overall ARPA-E research portfolio.

3.2.1 The empowered program manager culture

There are eight PMs at ARPA-E as of this writing; there are no office directors, who serve as an intermediate stage at DARPA between PMs and the director. Because ARPA-E is roughly the size of a large DARPA office it simply doesn't need them yet. Each PM picks his or her own inquiry areas; there is no overall technology plan.[36] However, PMs do form macro challenges within the sectors they initiate with the director—for example, seeking a zero emission, long range electric car. PMs therefore retain the flexibility of not being tied to a fixed ARPA-E-wide technology strategy. PMs also retain a great deal of control over their research portfolios, so are "empowered" like DARPA PMs, although they still have to persuade the director to support their program decisions. Director Arun Majumdar, has a reputation as a shrewd and intellectually adept judge and analyst. PMs say he insists on "complete technical and intellectual honesty;" as one put it, he is "a cricket batsman—he knows all the pitches." Thus, before a PM can select a technology project, he or she has to "sell" it to the director; the proposal often also has to survive rounds of brainstorming and vetting with PM colleagues. PMs have to have what they refer to as "**religion**"—they have a vision of where they want to take their portfolios, performing as vision champions, in order to sell their projects both inside and outside ARPA-E. Part of "religion," then, is that they must work on being vision implementers. ARPA-E PMs expressed the view that "religion" is the single most critical PM quality, aside from technical excellence. To summarize, ARPA-E uses DARPA's "strong program manager" model for research award selections and calls on its PMs to exert religious zeal in advancing selected technologies through the implementation stage. ARPA-E has purposely not created a formal personnel evaluation process for its PMs—as with DARPA, PMs say they are expected to "manage to results" and they are judged by the director and their colleagues—peer pressure—based on the outcomes, impact and results from the portfolios they select.

3.2.2 Additional mechanisms for talent support

ARPA-E has a **fellows program**, of five outstanding recent PhDs who help staff each PM and fill out the capability of each team. This institutional mechanism apparently may be creating a creative process of intergenerational contact and mentoring within ARPA-E, further ensuring that it becomes continuous education environment—a key feature for

[36] However, ARPA-E's enabling statute does require preparation of a technology "Strategic Vision Roadmap". America COMPETES Act (2007), Sec. 5012(g)(2), as amended by America COMPETES Act Reauthorization (2010), Sec. 904(b)(2).

creative R&D organizations. The new fellows also have been meeting together as a group to attempt to jell their own on new ideas. DARPA currently has no comparable group to help augment internal intellectual ferment.[37] ARPA-E is also considering creating its own team of **senior advisors**—"technology wisemen," in short—who spend time at ARPA-E through frequent visits and so contribute to the PM teams. The group would be somewhat analogous to DOD's "Jasons," a group of experienced technical experts brought into advise on major technical issues and problems (Finkbinder 2006), except that ARPA-E's Jasons would serve a similar function not for DOE in general but within an operational research agency, ARPA-E. This could provide a way to enable technology thought leaders from a range of fields to contribute to energy technology advance, pulling in new perspectives and new ideas.

3.2.3 Portfolio approach

All ARPA-E projects are selected, as discussed above, to be game changers—to initiate energy breakthroughs. However, within that broad requirement, as PMs assemble their portfolios around a particular challenge areas, PMs say they have found they need a "risk mix." They generally include some "out there" projects that may or may not materialize, that are very high risk, but where the technology is so potentially important that, although far from implementation, these are well worth pursuing. But for most other portfolio technologies, the PMs want to see that they could be implementable in a reasonable period—that they could reach a cost range that would facilitate entry and commercialization. Some PMs find they need to emphasize more early stage science in their portfolios than other PMs because their portfolio sectors require more frontier advances—so there is a mix, too, of portfolio balance between frontier and applied, science and technology emphasis. The grant approval rate varies between technology sectors, but (following the initial 2009 open ended offering discussed above), PMs indicate the rate ranges from 5 to 10%. That rate is likely too low for robust portfolios and will discourage some creative applicants; ARPA-E understands this, but is constrained by Congressional budget limits.

As with DARPA, ARPA-E PMs have adopted a **"hands-on" relationship with award recipients**, talking and meeting at frequent intervals to support their progress and help surmount barriers, and, when ready, to promote contacts with venture and commercial funding. In most research agencies, the job of the PM focuses on the award selection process; in ARPA-E, this is only the beginning. PMs view their jobs as technology enablers, helping their tech clients with implementation barriers.

B. Building a community of support

While Congress, in designing new science and technologies agencies, may get either the substantive design or the political design right, it does not often get both right (Bonvillian 2011a). In other words, the creation of an agency that is, from a public policy and substantive prospective, sound and effective as well as politically strong enough to survive, is a challenging policy design problem. ARPA-E was founded on a well-tested substantive model, the DARPA model; so as long as its leadership struggled to fulfill that complex design there was some assurance of success from a policy perspective. Although the history of DARPA clones is often not a positive one (Bonvillian 2007b, 5–6), ARPA-E's leadership has made the ARPA-E clone a widely acknowledged, successful substantive one

[37] When DARPA was first stood up it had a scientific advisory board and at times some of its Office Directors have empanelled such groups.

to date. However, ARPA-E's political design has been a more complex problem; from the outset it has faced a political survival challenge. In part this is because the Congress, on a budget cutback tear, has not fully embraced the need for an energy transformation. In part, it is because it is a small new agency fish in a cabinet agency filled with large agency sharks constantly on the prowl against funding competitors and turf incursions. These include such longstanding major entities as the Office of Science, the applied agencies and the seventeen national energy laboratories. To increase its chances of survival, ARPA-E needed not simply to avoid conflict with its large neighbors but to affirmatively turn them into bureaucratic allies and supporters.[38] Internal allies were not its only need—it also needed to build support outside DOE, from the energy research community it serves and from industry. All this had to be translated into Congressional support.

ARPA-E therefore has worked from the outset on **building internal connections within DOE**. The Department's R&D is organized into stovepipes. The Office of Science, a traditional fundamental science-only agency organized on Vannevar Bush basic research lines (Stokes 1997), funds its own nest of national labs as well as university research and reports to its own Undersecretary. DOE's applied agencies, including EERE, and fossil, electrical and nuclear offices, fund development work primarily through companies and report to their own Undersecretary. DOE's organization thus severs research from development stages, and historically very few technologies cross over the walls of the two sides of the DOE organizational equation, between basic and applied. In theory, ARPA-E could serve both sides by drawing on basic ideas coming out of the Office of Science that could be accelerated, pushing them to prototypes, then building ties with EERE and the applied agencies to undertake handoffs for late stage development and demonstration stages. ARPA-E could thus serve both sides by working to be a technology connector within DOE. There are potential downsides to playing the connector role—in some cases at DARPA it has been seen as inconsistent with performing the role of transformation instigator. However, ARPA-E has attempted this task, and met with success in forging a working alliance with EERE, a much larger \$1.5 to 2 billion a year applied agency. ARPA-E has EERE experts on its review teams and draws on their expertise; it has received strong support as well from EERE's leadership, who are working with ARPA-E on the handoff process described above (see further discussion below).

Integration with the Office of Science (SC) is still a work in progress. SC very much views itself as a basic research agency, and rejects work on applied research, assuming it is the job of other parts of DOE to manage those efforts. It funds a wide variety of basic physical science fields, aside from basic energy-related research. Managers at SC generally view themselves not as technology initiators but as supporters for the actual researchers located in SC's national labs and in academia. This represents a genuine culture clash with the energy breakthrough mission orientation of ARPA-E PMs. However, some attempts have been made to connect with the 46 new Energy Frontier Research Centers (EFRCs) formed by SC to focus on energy research in promising areas (Bonvillian 2011a, 315–316); two of ARPA-E's PMs report that they have selected one project each from EFRCs located at research universities.

Collaboration with the national energy labs has also proven a challenge. Because the labs are large employers, they have tended to become independent political power bases (Bonvillian 2011a, 304–305). However, ARPA-E has worked include labs in its research

[38] DARPA over time has attempted to achieve internal support from other defense R&D agencies. See Bonvillian (2009a, 220).

consortia,[39] hoping the labs will view it as not simply a funding competitor but a funding supporter.

3.2.4 Summit

ARPA-E has worked at building relations with venture capital firms and large and small companies, and with awardees and non-awardees, through two widely attended annual multi-day forums in the spring of 2010 and 2011.[40] These two energy innovation summits have become major technology showcase events in Washington, attracting large attendance and featuring prominent business, executive branch and bipartisan Congressional leaders in speaking roles. ARPA-E featured its awardees at these summits as well as other strong applicants who did not received awards but deserved attention. VCs and companies have swarmed around their technologies, building good will among attendees, whether they won awards or not. This has helped the growing field of energy technology highlight emerging technologies to potential private sector funders. The summits became, almost overnight, one of the biggest energy annual conference events in the nation, and have played a major role in putting ARPA-E on the map as an innovative agency. Importantly, by highlighting new energy technologies of interest to many sectors and firms, the summits have helped in building an advanced energy technology "**community**" around ARPA-E.

3.2.5 Support community

ARPA-E faced a major funding challenge in FY2011 when a change in political control of the House of Representatives and growing concerns over spiraling federal deficits led to cutbacks in federal agency funding. As noted, because ARPA-E received no funding in FY2010 (it received 2 years of initial funding in FY2009 through stimulus legislation) it needed affirmative legislation to survive. As a result of the goodwill that had been built in its first 2 years of operation, a community of support began to collect around ARPA-E to independently advocate for the agency's future with Congressional committees, including venture capital firms, large and small firms that worked with ARPA-E, and universities, all enamored of its research model. Thus, a political support system is growing, separate and apart from ARPA-E (which can't lobby under federal law) to back its efforts and continuation. It has reached a point where ARPA-E has received public support from some very prominent business leaders, including venture capital leader John Doerr of Kleiner Perkins, GE CEO Jeff Immelt, Microsoft's Bill Gates, and FedEx founder Fred Smith. The continued growth of such a political support community could help assure ARPA-E's political future.

In summary, not only has ARPA-E proven a strong substantive success to date from a public policy perspective, a political support base appears to be emerging that could help sustain it over time. ARPA-E could be in a position to achieve that rare combination, an integrated political design model, marrying political support with sound substance.

C. Technology implementation

ARPA-E's director and PMs are acutely aware of their difficult task in launching technology into the complex, established legacy sector of energy. DOE has a four decade

[39] America COMPETES Act (2007), Sec. 904(e)(3) authorizes ARPA-E to fund "consortia…, which may include federally-funded research and development centers" (FFRDC's—including energy laboratories).

[40] See programs for ARPA-E Energy Innovation Summits (2010, 2011).

history, as noted, of transitioning some technologies into commercial energy sectors but comparatively few at a scale where they would make a real difference in US energy consumption (National Research Council 2001). ARPA-E has therefore taken a number of steps to assist in taking its technology to implementation, commercialization and deployment:

ARPA-E PMs **consider the implementation** process for technologies they are considering; before they fund a project they evaluate the technology stand-up process and how that might evolve. Their focus is not simply on new technology, they seek to fund projects where they can see a plausible pathway to implementation. This is aided by the fact that ARPA-E PMs generally have both academic and commercial sector experience. On the commercial side, this experience ranges from work in venture capital firms and companies, to participating in technology-based start-up firms. This range of background in both academic and private sectors assists in understanding possible commercialization paths. However, ARPA-E is likely to need in the future to explicitly consider within its R&D program awards efforts to drive down the costs of technologies it supports to a cost level where they could reach commercial entry.

3.2.6 "In-reach" within DOE

ARPA-E is working on building ties, as suggested above, with applied programs in DOE so these agencies can be ready to pick up ARPA-E projects and move them into the applied, later stage implementation programs they run. ARPA-E's PMs have found that key to this DOE "in-reach" is building relationships between PMs and applied line scientists and technologists in the applied entities, particularly EERE, the Fossil Energy Office and the Electricity Office. This is a bottom-up connection process. Meanwhile, from a top-down perspective, the ARPA-E Director has worked in parallel at building ties between his office and the leadership of the applied agencies at DOE. But the PMs believe "bottom-up" connections are the key to "in-reach" success—without support deep in the applied bureaucracies, transfers simply won't happen, whatever the leadership levels agree to. For example, one ARPA-E PM went to DOE's Fossil office with his leading Carbon Capture and Sequestration funding projects, placing three Fossil experts on his review panel for the selection process and involving them in oversight work and progress meetings. He points out that in-reach is, "all relationships and people." There are similar bottom up approaches to build collaborative relations between ARPA-E and EERE on wind and other efforts, and with the Office of Electricity. ARPA-E's Director is also giving consideration to working top down with DOE applied agencies to create more formalized interagency groups around particular technology strands for collaboration across DOE stovepipes. The hope is that the groups can serve as "lead customers," because the resources in applied agencies could promote later development stages.

But the applied agencies can only take ARPA-E technologies so far. DARPA learned how to work with a "customer" as it tried to collaborate with and encourage the military services to adopt its technologies in their procurement programs. While, as discussed above, this isn't necessarily easy, DOD has acted in many cases as the initial market for DARPA technologies. DOE doesn't offer comparable internal "customers" for ARPA-E technology advances. The efforts to undertake in-reach within DOE are an attempt to improve this situation, and can assist in moving into the proof of concept, prototype and demonstration stages. The applied offices, which largely fund development work at companies, can also assist ARPA-E with follow-on company support for continued engineering advances for ARPA-E technologies. Learning what it actually means to have and work with a “customer,” as DOD does in multiple ways, may prove a vital skill set for an effective R&D agency like ARPA-E, given its concern about affecting technology outcomes. A customer-driven approach, even in the stage of breakthrough research, can be an important driver in technology advance. ARPA-E’s leadership and PMs understand that necessity in the energy technology sector. This is shaping up as one of the central questions for ARPA-E’s future success, explored in Part 4, below. While DOE “in-reach,” discussed above, is part of the answer, another logical step for ARPA-E is to connect with DOD agencies potentially interested in ARPA-E technologies for DOD needs (Alic et al. 2010; Bonvillian 2011b), given the latter’s depth in testbed capabilities and first market opportunities, which remain gaps in DOE’s innovation system.

ARPA-E is in fact working on building **ties to DOD for testbeds and initial markets**. DOE has executed a Memorandum of Understanding with DOD, but implementation is still largely at the discussion stage and results are still “in progress.” DOD and ARPA-E have recently partnered on two projects, however, in battery storage and power electronics, for a modular energy storage system that can rapidly charge and recharge, and for new ways to combine onsite renewable generation with microgrids for use in military installations (Hourihan and Stepp 2001). DOD’s own efforts on energy technology are just now coming into effect, but it is pursuing energy technology advances to meet its tactical and strategic needs, as well as to cut energy costs at its 500 installations and 300,000 buildings.[41] As an indication of its serious intent, ARPA-E has on staff a technologist with significant defense contractor experience (he is on the “Commercialization Team”—see discussion below) working full time on collaboration with DOD. Since the offices in DOD working on energy technology are in the process of connecting with each other, ARPA-E is helping in convening these groups across the services. The potential role of DOD to test and validate and to offer an initial market for new energy technologies is well-understood at ARPA-E, offsetting the fact that its home organization, DOE, generally does not engage in the innovation process beyond late stage development and prototyping support.

3.2.7 Commercialization team

ARPA-E has assembled on staff a separate team working full time to promote implementation and commercial advances for ARPA-E technologies. These team members work with particular PMs on the most promising technologies emerging from their portfolios. ARPA-E, in effect, has added a variation to DARPA’s famous “Heilmeier Catechism”[42] by requiring PMs and their Commercial Team-mates to “tell me how your story will end and how will you get there?” The tactics this team develops in implementing technologies can include creating follow-on approaches for ARPA-E funded technologies through in-reach with DOE applied programs, connections to DOD testbeds and procurement, as well as connections to VCs and interested company collaborators, or combinations of these. Their work includes identifying first markets and market niches for ARPA-E technologies.

[41] See, for example, Hourihan and Stepp (2001) and testimony of DOD Deputy Under Secretary for Facilities and Environment Dorothy Robyn (Robyn 2010).

[42] George H. Heilmeier was Director of DARPA from 1975 to 1979. See his “Heilmeier Catechism” of questions about proposed research projects. Heilmeier Catechism (1975). See, generally, Heilmeier (1991).

3.2.8 "Halo effect"

ARPA-E is consciously taking advantage of the "halo effect" where VCs and commercial firms pick up and move toward commercialization the technologies that are selected by ARPA-E as promising. In other words, the private sector views the ARPA-E project selection process as rigorous and sound enough that it is prepared to fund projects emerging from that process. ARPA-E recently announced, for example, that six of its early projects, which it funded at $23 million, subsequently received over $100 million in private sector financing (Department of Energy 2011a). This effect has been seen before at DARPA and at the Department of Commerce's Advanced Technology Program (revised in 2007 as the Technology Investment Program). The VC or financing firm will perform its "due diligence" regardless, but ARPA-E's selection helps in identifying and, in effect, validating, a candidate pool.

3.2.9 Connecting to the industry "stage gate" process

The stage gate[43] process is used by most major companies in some form in the management of their R&D and technology development. In this approach, candidate technology projects are reevaluated at each stage of development, weeded-out and only what appear to be the most promising from a commercial success perspective move to the next stage. This is not a process ARPA-E employs; like DARPA (as discussed above), it places technology visioning up front in its process (Carleton 2010) and adopts a high risk/high rewards approach to meet the technology vision. Although ARPA-E's is a more fluid and less rigid, vision-based approach, it has recently started to work with its researchers to get their technologies into a format and condition to survive in the industry stage gate process. For academic researchers in particular, this is not a familiar process. Because most early generation energy technologies are component technologies, and will have to fit into existing systems and platforms controlled by existing companies (Weiss and Bonvillian 2009, 185–190), ARPA-E PMs are recognizing that many of the technologies it nurtures must slot into the stage gate industry practice if they are going to link with industry, so it is considering how to prepare its technologies (and technologists) to withstand this process.

3.2.10 Consortia encouragement

Aside from stage gate connections to industry, in a different kind of outreach effort, ARPA-E is building an additional industry connection step between the firms and academics that it works with and the industries they must land in—consortia promotion. ARPA-E tries to pave the way for acceptance of its new technologies at firms by working to encourage companies that work in similar areas to talk to each other on common problems, including on technology solutions that APRA-E's current or prospective projects could present. This is another facet of its community building efforts referenced above. For example, its PMs are working on this approach with groups of companies potentially interested in ARPA-E's carbon capture and sequestration (CCS) and battery project portfolios. The kinds of problems discussed are not the researcher's "secret sauce" but common issues of organization and general technology advance, including technology needs and standards relevant to all participants—both the researchers and the firms that

[43] See, for example, Cooper et al. (2002).

may be interested in their emerging technologies. This approach helps prepares the ground for technology implementation and acceptance.

3.2.11 Prize authority

Following in DARPA's footsteps,[44] ARPA-E, has authority (America COMPETES Act Reauthorization 2010, Sec. 904(f))) to offer cash prizes for meeting technology challenges and is considering how to use it. This could be an additional creative tool for technology acceleration and implementation but may require unique adaptations to fit the legacy energy sector.

To briefly summarize, then, ARPA-E has not only worked to replicate elements at DARPA, but it has attempted to build new elements in its innovation ruleset as it confronts unique features of the energy sector where its technologies must land, and of the DOE bureaucracy its must work with. These new elements can be grouped into three broad areas, as detailed above: in sharpening the research visioning, selection, and support process; in building a politically survivable support community; and in the implementing and deployment process for its technology advances. Organizational tools in these categories being developed at ARPA-E present lessons that could be relevant and useful to other innovation agencies.

3.3 Relevance of the additional DARPA features (cited above) for applicability to ARPA-E

In the discussion of DARPA, above, a number of DARPA capabilities not generally noted in the literature to date have potential relevance to ARPA-E in strengthening its operations and enhancing its future capabilities. These are organizational options not necessarily relevant to ARPA-E's current start-up phase but that it could consider as it continues to evolve. They may also serve as guideposts to help ARPA-E fill gaps and improve its performance. A series of the additional DARPA capabilities discussed above in Part 2, are reviewed below for relevance to ARPA-E.

3.3.1 Multigenerational technology thrust

As noted, DARPA has not only been able to undertake individual technology projects, but to work over an extended period to create enduring "motifs"—generations of new applications within a technology thrust that have changed technology landscapes over an extended period. Examples, as noted, include its work in IT, stealth, and precision strike. The approach ARPA-E is now implementing of projects with a 3–5 year duration based on the expected "life" of its PMs, will likely require supplementing with a multigenerational model because many energy technologies will require ongoing advances before they reach maturity and optimal efficiency. For example, ARPA-E understands lithium ion generation battery advances likely will be displaced by further generations, yet the 3–5 year project approach will not get ARPA-E to the subsequent generational battery advances without further work on its technology organization. ARPA-E has settled on a series of program portfolios which could provide a basis over time for thrust areas, as summarized above.

[44] See, for example, DARPA (2009) (Network Challenge); DARPA (2007) (Urban Challenge).

However, it has avoided a technology strategy to date, viewing it as a limiting factor on its PMs' ability to respond to technology opportunities; it may have to consider such an approach to manage the handoffs in the technology sectors it is pursuing as PMs succeed each other. Otherwise, it may not be able to field a multigenerational technology thrust capability to meet the inherently long term challenges of most energy technologies.

3.3.2 Strategic relations between technologies

DARPA has launched related technologies that complement each other, which help build support for the commercialization or implementation of each. For example, its stealth technology advances complemented its precision strike advances, with both serving as mutual enablers. Launching bundles of related technologies could similarly alter the energy landscape. For example, new batteries coupled to biofuel advances could significantly enhance the energy consumption effects of hybrid vehicles, and storage advances are crucial enablers for enhanced renewables technologies. As ARPA-E builds out its technology portfolios, it could work to envision linked and crossover technology advances, supporting complementary efforts.

3.3.3 Confluence with an advocate community

DARPA created a broad and sizable community over time from its PM "graduates" and numerous award recipients in both universities and industry. This community was trained in the DARPA model and technology approaches, and in turn constituted a sizable group of change agents that invaded and altered numerous technology sectors. In other words, DARPA has become far larger than simply its on board staff. ARPA-E started out a much smaller scale than DARPA, but needs to consciously work to build its community to make them not only supporters for its continuation (see subsection B discussion on its support community, above) but an allied group of change agents. Its technology task, because it is innovating in a legacy sector, may prove considerably more daunting than DARPA's, so it will need over time to field an army. Its summit (discussed above in subsection B) is a useful initial organizing mechanism in this regard, but ARPA-E will need additional mechanisms to achieve this.

3.3.4 Connection to larger innovation elements

DARPA has spawned new technologies that arose and converged with venture capital and entrepreneurial support and led to new economic sectors, particularly in IT fields. Thus, DARPA has been able to play an intermediary role with industry, able to make its advances reinforce sectors that support them, creating a mutual synergy. ARPA-E will need to consider this approach with the firms and sectors it collaborates with, including those providing capital support, as its technologies advance. It is already moving in this direction, as the discussion of the new elements in the model suggest, becoming an actor connected with larger innovation efforts. It can play an instrumental role in these larger innovation systems, seldom as a sole actor, but instead as a team creator and player. The DARPA approach where its technologies spawned numerous IT firms which help effectuate its overall vision, and are linked to other supporting elements in DOD, offers lessons for ARPA-E. As its technologies progress, it will need to consider the appropriate models for this kind of confluence in the complex energy sector.

3.3.5 Takes on incumbents

DARPA historically invaded territory occupied by companies or bureaucracies when it needed to foster technology advances. Perhaps its most famous example, as noted, is how, in an effort to develop new command and control systems, it drove desktop personal computing and the internet to displace the IBM mainframe model, in a classic example of disruptive technology launch (Waldrop 2001). Because energy is a CELS—a complex, established, "legacy" sector—conflict with legacy firms with established technologies will be frequent and inevitable for APRA-E. The energy legacy sectors probably see this coming—the only opposition, for example, to the ARPA-E concept when it was proposed in the National Academies' *Gathering Storm* report of 2006 was from the CEO of a major oil company (National Academies 2007, 152–153). While DARPA faced internal bureaucratic battles to launch its technologies, it only occasionally faced industry conflict because it tended to stand up technologies in new territories rather than in existing legacy sectors (Bonvillian and Weiss 2009; Weiss and Bonvillian 2011). ARPA-E, however, will likely face incumbent technologies and firms across its technology portfolios. Accordingly, it will need to further build its support communities if it is to be successful in launching its technologies (see discussion on community building in subsection B, above). In addition, it will need to continue to enhance its technology implementation capabilities (subsection C, above and Part 4, below).

3.3.6 First adopter/initial market creation role

DARPA has frequently undertaken a technology insertion role; in coordination with other parts of DOD it has been able to create initial markets for its new technologies, allowing the Department to serve as first technology adopter. As discussed above (in subsection C), DOE offers no comparable first market for ARPA-E technologies. Given DOD's interest in energy technology advances, it could serve as an initial market. ARPA-E will need to develop further strategies to find first adopters and initial markets because the lack of track records on costs and efficiencies constitutes a serious barrier to commercializing and scaling new energy technologies.

3.3.7 Ties to technology leadership

DARPA has been particularly effective when it is tied to senior leaders that can effectuate its technologies through DOD or elsewhere. ARPA-E is been effective to date, as discussed above, in securing a network of leaders in the Department, in the White House and on Capitol Hill, to support it, but will need to continually work to bolster its ties to energy decision makers in key places throughout the government who can help it fulfill its mission.

3.3.8 Doesn't necessarily launch into a free market

DARPA has embedded itself in a connected innovation system, taking advantage of DOD's ability, as noted above, to operate at all stages of innovation, from research, to development, to prototype, to demonstration, to testbed, to initial market creation. Therefore it often has been able to launch technology into an integrated system—it doesn't have to toss its prototype technologies over a wall hoping they will be picked up in the private sector, it can ready them for scaling in the private sector, or simply stay in military markets. While, as discussed in Part 2, this often isn't easy, DARPA has made this work. ARPA-E recognizes that because it will be launching its technologies into a CELS, it may be able to use DOD testbed and procurement roles, as discussed above, to further its advances. It can also fund creative companies that have capability to commercialize its technologies into products, and it can otherwise guide its technologies into commercialization, building portfolios of technologies for in depth technology thrusts into emerging markets. It can, in addition, leverage its technologies against regulatory mechanisms, such as fuel economy and appliance standards, or state renewable portfolio standards. These and additional tools will need to be sharpened.

3.3.9 Ahead of the game

Just as DARPA has tried to stay in front of Congressional interference and micro-management, ARPA-E has worked to develop coherent narratives about its technology approaches that show its projects to be "ahead of the game." Like DARPA, it has worked to avoid a situation where Congress captures the narrative and forces ARPA-E involvement. In the next several years, however, particularly as some of its projects approach implementation stages, ARPA-E will need to demonstrate success and further refine its story.

In conclusion, ARPA-E presents an exciting and innovative emerging agency model. It has successfully incorporated the basic operating rules from DARPA into its own ruleset. In addition, because it must operate in the demanding energy sector which is different from the sectors where DARPA operates, it has evolved a group of its own new rules. There are also useful future lessons for ARPA-E for its organization and strategy from a series of DARPA approaches that have not been covered in depth in the literature on DARPA. Finally, while ARPA-E has taken important steps in the back end of the energy innovation system to implement technologies it nurtures, additional implementation efforts will be needed. This problem is discussed in detail below.

4 The remaining technology implementation challenge for DARPA and ARPA-E

Both DARPA and ARPA-E face a profound challenge in technology implementation. For DARPA, the Cold War era of major defense acquisition budgets is long gone, and defense "recapitalization"—replacement of existing generation of aircraft, ships and land vehicles with new defense platforms—is evolving at a glacial pace. Finding homes for its evolving technologies, therefore, has increasingly become a difficult task for DARPA. Because technology transition was once a difficult but comparatively straightforward task for DARPA, it has not yet fully faced up to the implications of how complex it has now become. ARPA-E faces a technology transfer problem of the first magnitude: the U.S. has a failed history of moving technology advances into CELS (complex established legacy sectors), including in energy. U.S. Presidents have been calling for energy independence for four decades; the situation has only gotten worse, probably an unparalleled U.S. record for technology failure.

The innovation system used by the defense sector has led most major innovation waves of the 20th century: aviation, electronics, nuclear power, space, computing and the internet (Ruttan 2006a). In the process, DOD has built a systems approach to its technology advances—it operates, as noted at each stage of the innovation process: R&D, prototypes, demonstrations and testbeds, engineering and incremental advances, and initial market creation. At each stage, it has created institutions and functions that enable this systems approach. There are essentially four of these sets of institutions and related functions that match the innovation stages: (1) At the breakthrough R&D stage, DOD uses DARPA, which supplements more traditional service R&D agencies; (2) At the prototype/demonstration/testbed stage, it uses the services, including their system of service labs (FFRDC's); (3) At the engineering and incremental advances stage, for its technologies and the platforms that use them, DOD uses the services' development and procurement programs, based on DOD's "requirements" system[45]; (4) For initial market creation, DOD uses its services-based procurement programs. While the handoffs between these DOD institutions and functions are rarely smooth, it is nonetheless a comparatively integrated system. DOD periodically supplements this system with efforts to launch technologies through civilian markets—DARPA, as noted below, has played a particularly important role in this approach.

An energy technology transformation is going to require a systems approach comparable to DOD's. DOE now has a DARPA-equivalent for the breakthrough R&D stage, complementing other DOE research entities. How will it handle the other three innovation system stages it must put into place to implement its technologies? The discussion below first reviews in detail the challenges DARPA faces in making the DOD innovation system work to implement technologies it originates. This provides lessons for ARPA-E's implementation challenges as well.

A. The implementation problem: launch pathways for DARPA and ARPA-E through military procurement, established industry and the entrepreneur/VC model

Can ARPA-E succeed with its focus on transitioning the results of its research to commercial industry, in comparison to DARPA's main mission of developing technology for defense capabilities? The information technology examples discussed in this paper demonstrate that DARPA, using a technology push approach, did develop a successful university-private sector approach for supporting these technologies. While DARPA faces a problem of the "valley of death" between its research and late stage development, there is an at least equally daunting problem of "market launch" lurking behind it.[46] DARPA has five decades of history in attempting to launch its technology using primarily three pathways: military procurement, established industry, and a comparatively new entrepreneur/VC model that DARPA itself helped enable. The launch difficulties for DARPA for each of these pathways will be explored in detail below. Because ARPA-E is too young to have its technologies reach the implementation stage, the difficulty of its market launch problems are less clear, so the discussion below will focus on DARPA. At the close of this discussion, future technology implementation issues for DARPA will be considered based on these launch pathway issues, followed by a discussion of how DARPA's lessons can provide guidance for ARPA-E.

4.1 Market launch in the military sector

DARPA's main mission implementations, such as unmanned air vehicles, large-scale radars for missile defense, and standoff precision strike systems, were effected in a very different environment than commercial industry. Military procurement has enabled implementation of its military technologies as well providing initial markets for a number

[45] See discussion of this engineering stage at DOD in Alic (2011) and Gholz (2011).

[46] The concept of "market launch" is developed in Weiss and Bonvillian (2009, 14, 20, 34).

of technologies implemented primarily through the commercial sector. Importantly, even with the strong defense imperative and backing from high-levels in DOD for these programs, their implementation, as noted in Part 2, generally was difficult, costly and time consuming. With only the very exceptional implementation of stealth technology as the F-117A, which was, as noted above, personally overseen by Under Secretary of Defense William Perry, most DARPA-developed military capabilities faced difficult transitions into military service acquisitions. Notably, these transition problems can be attributed to differentiating factors in military systems compared to commercial products.

Major DoD systems differ substantially from most commercial products: Major DOD platforms and systems are massive undertakings compared to almost any other industry endeavor.[47] DOD's recapitalization rate through its procurement programs has been in sharp decline since the end of the Cold War. It builds ever fewer major systems and each system is likely to be fielded over decades and thus have to meet or respond to projected requirements that are difficult to ascertain and are likely to change in unforeseeable ways.

Commercial and DOD product development processes are substantially different: DOD systems are contracted efforts implemented by third parties through program offices. The program is funded based on front-end decision processes based on "needs" criteria and some assessment of feasibility prospects—but these are often at a high level and often with limited means to assess them within the contracted phase. In contrast, industry generally makes decisions concerning its own money and investments directly related to developing and implementing the product itself (in conjunction with suppliers and, potentially, outside investors).

However, this may have changed significantly for commercial industry in recent years, as more of the development is based on outsourced subsystems and components, and even the development itself may have been outsourced. The distributed manufacturing model may have changed the connectivity within the firm between decision and performance and perhaps changed the motivations concerning resource decisions. At the same time, DOD contractors have also become more distributed and diffuse, with the concept of lead system integrator and a dispersed supply chain, so there may be interesting lessons learned between defense and commercial firms as they both negotiate this new approach to enterprise management.

4.2 Market launch through established industry

Although DOD has launched many incremental advances through its service procurements with large firms, for the reasons discussed below, DARPA has had limited success launching its breakthrough advances into established industry.

Commercial and DOD/DARPA technology risk profiles are substantially different: DOD through DARPA has implemented technology push systems that are new and

[47] There are very few industry tech developments at a scale comparable to those of major defense systems. One recent one is the Boeing 787 Dreamliner passenger aircraft. Notably, that development has experienced major problems in cost and time to product (it is 3 years late and facing on the order of $12 billion in overruns), some of which can be attributed to problems of transitioning and implementing new technologies. See, Gates (2010). It also appears that Boeing, taking a chapter from the IT sector and its distributed global manufacturing model, hoped to become a global systems integrator to spread and reduce its aircraft development risk, since the capital costs mean each new plane launch is usually a "bet the company" experience. However, complex aero technologies have not yet proven as susceptible as IT to global production distribution. The complexity of managing a global sourcing network for the 787 has been relentlessly problematic.

unprecedented, compared to industry, to achieve technological superiority with limited prior knowledge or experience with the proposed technology or its use. Several such systems have been developed by DARPA, as a technology push organization, with minimum to little explicit interest or involvement of the services, the "recipient" developer. Often the push for development is a "top-down" mandate from OSD, as noted above, or even Congress. Such systems—consider precision strike—are often developed by DARPA as the "innovation hub" explicitly to be disruptive or transformational, but their very nature makes them much more risky, not just from a technological perspective, but from the standpoint of transition and operational risk.

However, such developments still must be implemented within the existing service acquisition processes, which are relatively cautious about taking on new capabilities beyond their internally developed systems. Often the recipient service has very different perspectives and interests from DARPA, the technology developer, on the priorities and value of the technology and its potential application. There are many instances in which the recipient service actively has opposed the technology before being mandated by those at higher levels in OSD to accept it, as was the case, as noted above, with stealth, tactical UAVs, HALE UAVs, and tactical satellites. In some cases the service has actually successfully fought the technology or so poorly implemented it that the technological capability eventually succumbed; examples include Discoverer II, Arsenal Ship, and the Aquila UAV.[48] The recipient service organization is loath to spend the additional resources required to "de-risk" the "revolutionary" concept particularly if it disrupts or counters its accepted operations and capabilities, and distracts resources that it sees as needed for these.

Technology push systems usually offer little information to guide their actual use and deployment; what level of capability to achieve at what level of performance is difficult to define or assess. Thus, "knowledge risk" may be a major impediment to the adoption of such radical technologies. While World War II and the Cold War forced DOD to innovate in an atmosphere of crisis, with the end of the Cold War and short term symmetric threats, there is a diminished sense of crisis, and a corresponding decline in impetus for the services to adopt DARPA's transformative advances, exacerbating its technology implementation problems.[49] This is not simply a military problem; the "knowledge risk" and limited sense of crisis are reasons why industry is usually adverse to radical as opposed to incremental innovation; other reasons are discussed below.

Industry is almost always highly constrained on investments into new endeavors: Within the firm there is constant competition for resources, thus industry generally entertains low technical risk. Firms actively assess risk and value in a series of spaces. Assessment occurs between the current product, process development and the new endeavor. For example, SUN Microsystems faced a major resources crunch to maintain its current product competitiveness that almost prevented the development of the next generation SPARC workstation (Bertrand and Van Atta 1993). Current product demands dominate production investment decisions, with new risky products requiring external corporate support, which often isolates their development. Assessment also occurs between current product divisions and new divisions or enterprises needed to foster the new products. In an example of failed assessment, DEC, after stunning success in microcomputers, was not able to adequately

[48] See Knox (1999) for a thorough case analysis of the difficulties in the U.S. Army implementation of tactical UAVs.

[49] Vernon Ruttan has raised the concern that with the post-Cold War decline in impetus in defense innovation, the U.S. innovation system may not now be strong enough to launch new breakthrough technologies in either the public or the private sector (Ruttan 2006b).

assess and manage the transition to desktops and ever more personal computing through a crisis of imagination and innovation organization (Schein 2004).

These risk and value criteria are constantly being evaluated with strong prospects that a system development in industry will be cancelled or severely scaled back if it starts to go off track in any key risk dimension. This is often undertaken through the widely-adopted industry "Stage-Gate" process for R&D management, which constantly screens and weeds out potential innovations (Cooper et al. 2002). For industry time-to-product is crucial. The space between market entry vs. the competition is a major criterion; there is a difference in being first and not being in the game. On the other side of this coin, there are also sometimes cost and learning advantages to launching improved products as first follower to market. The space between production costs and market price is also crucial. If new underlying technologies for products show signs of cost escalation and seriously erode profitability, the product is highly likely to be cancelled.

Industry development of technology push systems is rare: It is difficult given the above issues, as well as problems of business constraints on finance, time-to-product, and internal and external competition. Technology push developments within existing firms are usually incremental, with one new element or component introduced, rarely a major new integrated system, and market-entry is staged carefully relative to "creating" demand. As Ruttan has explored, incremental advances usually respond to calculated market niches and opportunities (Ruttan 2001), while breakthrough innovation can rely on few such market calculations because the transformative product is unanticipated and disruptive to markets. There are exceptions, but even Apple's properly vaunted latest products fit this model. The iPod was a breakthrough combination of a good MP3 player with a new music access system; its iPad was a handheld notebook coupled with broader media access, communication and computing capability. Both were breakthrough products because of the way they combined previously unmixed technologies, but they integrated mostly available and comparatively mature components into new forms and combinations, rather than introducing multiple new technologies. In addition, Apple also relied on distributed global manufacturing to further cut its production risks and to share development costs, allowing it to move rapidly from design to production to quickly capture market share.

Technology push developments within existing firms are usually run differently from the rest of the firm, with different a management structure and oversight, such as through the "skunkworks" approach (at Lockheed and for IBM's PC desktop line), through the R&D centers at such large firms such as IBM, GE and P&G, or through the innovation hub notion. Often such developments report to headquarters and are separate from existing product divisions. Their transition efforts are usually accomplished with strong involvement from central management; while this may be a necessity (Bennis and Beiderman 1997, 206–207), it tends to disconnect production and the new products they may have to produce, reducing the potential for "learning by doing."

4.3 Launching through the entrepreneur/VC model: the role of entrepreneurs, startups and VCs

Technology push developments in industry are often undertaken outside of existing firms by start ups: Frequently, these are led by entrepreneurs who left existing firms or obtained technologies from existing firms or government research, forming startups and using risk capital from outside investors, usually angel investors then venture capitalists (and sometimes as corporate sponsored "spin-outs"). This entrepreneurial/VC system was a US model dating from the 1960s and 1970s. It was the way the US launched the IT innovation wave (then the biotech wave), giving it a significant world competitive advantage and enabling one of the strongest economic growth periods in 20th century US economic history, in the 1990s. Although many nations have envied this model, few have been able to stand up comparable capability. DARPA played a very significant role its creation because its IT advances coincided with its development, creating strong mutual synergies. This Entrepreneur/VC model was the element that enabled DARPA to get around the profound difficulties of trying to introduce its innovations into established industries, with all of the complexities and entry problems listed above. Thus, DARPA did an end run around the established industrial sector in introducing IT.

However, the entrepreneurial/VC sector has it own limits and requirements, too: Such start up ventures are subject to a different set of rules and practices driven by the outside investment community, with well-defined risk assessment and mitigation strategies and practices. Risk of failure is accepted but with payoff for success correspondingly required to be very high. The investment decision is made early in development and the endeavor is "given" high-level management support by investors to achieve transition, e.g., Scott McNeely was placed as CEO for SUN Microsystems by venture capital investor Vinod Khosla of Kleiner Perkins. Displacement of the initial inventor team with more experienced management is frequently the price start ups pay for VC support.

VC investors expect relatively quick payback, so VCs need to be able to move their firms to Initial Public Offerings (IPOs) within a few years of their investments. Thus, VCs won't support technologies more than 2 or 3 years from production, and not much longer than that to projected profitability, which are prerequisites to launching an IPO and getting their investors' money back. This worked well in the IT revolution, when new applications could build on an expanding sector as the IT innovation wave gathered momentum and expanded in many directions. Similarly, it worked in biotech, with larger pharmaceuticals ready to produce or buy out biotechs once their technologies were in range of FDA approval. Biotech, while longer term than IT, has recognized stages that correspond to research advances and FDA trials that create a series of exit ramps that help investors manage risk. However, the Entrepreneur/VC model, with these relatively short or staged timetable requirements for spinning off to the IPO stage, is not readily adaptable to CELS—complex, established, legacy sectors, such as energy or manufacturing. Even where DARPA sponsors new technologies that can lead to "open territory" innovation not limited by legacy incumbents, the model requires a significant emergence period before it will accept other technology—it took from 1969 to around 1992 before the internet revolution began to scale.

Therefore, technology push developments in both established industry and through the entrepreneur/VC model are often undertaken using support and subsidies from the government to provide initial buffers against technology and market risks, providing early customer and production learning.

4.4 Review of DARPA launch pathways and implications for ARPA-E

The above discussion has focused on DARPA, which has 50 years of experience trying to move its technologies into implementation. A major embedded point in the above discussion is that DARPA's technology transition is not going to get any easier. Essentially three DARPA launch pathways were identified above: launch through DOD procurement, through established industry, and through the entrepreneur/VC model. Bootstrapping its technology advances onto military procurement may prove more difficult for DARPA over time, as discussed. The services already tend to resist disruptive technologies, and this tendency may accelerate as budgets decline and procurements stretch out.

DARPA’s ability to launch technologies initially through established industry has never been as strong because, as discussed, their economic constraints make them risk averse, rarely willing to embrace disruptive technologies. DARPA has enlisted established firms through the military procurement system, however, and developed important technologies through such entities as Lockheed’s Skunkworks and IBM’s research division. It has also supported advances through industry consortia, in semiconductors, for example. Occasionally, in its projects, it will try to tie smaller firms with larger ones, with the larger firms sometimes leading the research management, to facilitate technology scaling. However, as will be explored in more detail in the next section below, DOD faces a challenge to its overall technology leadership due to the decline of the defense manufacturing base, which will affect the production process as DARPA technologies are implemented. This makes this established firm sector a DARPA problem not primarily through initial launch but later implementation of its technologies.

The third launch pathway, through the Entrepreneur/VC model, has always provided synergy for DARPA, particularly for the IT advances it has sponsored. While this model adapts well to continued IT advance, its comparatively short and staged timeframe for obtaining capital, through VCs and IPOs, limits its abilities to support the launch of technologies into CELS. In addition, significant pump priming may be required for DARPA to launch new technologies into new unoccupied territories because while the entrepreneurs may be ready, their supporting VC and IPO capital system may take time to sell new ideas to their investors. Thus, DARPA faces serious constraints for implementing its technologies on each of its available launch pathways.

Although ARPA-E is still too young to be pushing products into energy markets, the DARPA launch pathways offer important lessons. Concerning the military procurement pathway, this offers promising implementation opportunities to ARPA-E, as discussed in Part 3, which it is already starting to pursue. The key will be whether DOD’s interest continues or wanes in solving the strategic and tactical operating problems created by its energy dependency, and whether energy efficiency cost reductions and grid security needs can be achieved in reasonable time periods by evolving energy technologies. Concerning launching technologies into established industry, ARPA-E faces all the challenges listed above that DARPA faces and more. Energy is a classic CELS, and new technologies launched into such legacy sectors generally have to be able to compete on price on day one (Bonvillian and Weiss 2009). Although DARPA could largely ignore established industry due to the inadaptability of breakthrough technologies to commercial constraints, because the established energy sector is there and itself needs to be transformed, ARPA-E can’t ignore it, it must confront it. If ARPA-E is to have hopes of achieving this very challenging entry, it must, at a minimum, incorporate into its R&D programs efforts to not only perform research but to drive down the costs to competitive levels to enable entry into the energy CELS. This is one of the most challenging technology tasks any US innovation agency has faced, and there is a long history of problems with such efforts at DOE.

Finally, ARPA-E also faces challenges in utilizing the Entrepreneur/VC launch pathway. This is a logical pathway for ARPA-E to emphasize, and DARPA has done so very successfully. However, there are two major difficulties ahead. First, the timeframe for entrepreneurs and their start ups, if fueled by VC and IPO capital, is probably on a much longer timetable for successful commercialization than for IT or the staged biotech sector. Because energy is such an established sector, and new technologies correspondingly have so many barriers to overcome, technology entry may take a long time, well beyond the

3–5 year timeframe VCs are organized around. Second, most new energy technologies are component technologies, they have to fit into existing systems and platforms—advanced batteries have to fit into cars, fuel cells into homes or commercial buildings, carbon capture technologies into utility systems. The established industries or sectors that control the platforms or systems may all too often be reluctant customers, unwilling to absorb the risk of accepting new technology components until they are fully proven and demonstrated, and costs clear. Without access to a strong testbed system for these demonstrations, the entrepreneur/VC model is unlikely coalesce around most such technologies emerging from ARPA-E.

B. The problems of manufacturing and testbeds

To summarize, the technology implementation challenge faced by both DARPA and ARPA-E is a profound one, although different for each agency. DARPA can still try to use DOD as an initial market, although, as noted above, that is harder than in the past. It has always also tried alternatively to stand up its technologies in the civilian sector, where its success in IT is the leading example. In this "dual use" approach, the civilian sectors pick up the DARPA technology and fund the ongoing engineering and incremental advances, as well as related applications, so the military leverages from the civilian sector, cutting its own development costs and creating a range of applications that the military itself could never evolve. As long as DARPA is innovating in new as opposed to established sectors, that model, while never easy and longer term, can be made to work. However, DARPA needs to devote new attention to how its innovation can move into both military and civilian markets, given the underlying problem discussed above for its launch pathways.

For example, DOD has long relied on the strength of the U.S. industrial production base, which has been the world's strongest since the late 19th century. However, China has now likely passed the U.S. in manufacturing output[50] and the production function for U.S. industry is globalizing. U.S. military superiority has long relied on U.S. technological superiority, and its corresponding ability to implement and mobilize that superiority through on-shore production—that era may be shifting (Van Atta et al. 2005). Accordingly, DARPA, as suggested in Part 2, is now looking hard at whether new manufacturing technologies and processes could improve U.S. manufacturing productivity to a point where the U.S. could retain production leadership in critical sectors, a key military capability (MIT Washington Office 2010, 4–6). This, however, is inherently dual use technology which would have to be implemented in the private sector. DARPA needs to consider, in parallel to its manufacturing R&D efforts, the implementation tools at DOD it could make use of, including DOD's Mantech program and the Defense Production Act, along with DOD's defense procurement authority.[51] Manufacturing is just one of many technology implementation problems DARPA will face in the future, which may compel it to examine additional implementation models.

As noted above, ARPA-E likewise faces major implementation problems as it launches technologies into the energy CELS. It is working on, as discussed in Part 3, above, a number of interesting new mechanisms to assist in this task, including: consideration of

[50] IHS Global Insight (2011) states that in 2010, China accounted for 19.8% of world manufacturing output (in current dollars), a fraction ahead of the United States' 19.4%; China's manufacturing sector grew 18% in 2010 and the U.S. at 12%; over 2008–2010 China's manufacturing sector grew at a pace of 20.2 percent per year, while the United States grew at 1.8 percent and Japan, the third largest, at 4.25 percent. See also, Baily (2011) and Norris (2011).

[51] DOD's Office of Manufacturing and Industrial Base Policy is playing a lead role in this area. Dept. of Defense Office of Manufacturing (2011).

implementation early in its selection process, selecting PMs with venture or start-up experience, an "in-reach" effort within DOE for implementation support from DOE applied agencies, forming its own commercialization team, working with the industry stage gate process, assisting in forming industry consortia and connecting with DOD for testbed and initial market creation for its technologies. While both DARPA and ARPA-E move technologies down the innovation pipeline to the prototype or small scale demonstration stage, neither agency itself has the financing authority to enable initial market commercialization of its potentially breakthrough technologies. Although, as noted, DARPA can work to leverage DOD procurement for product introduction for military or dual use technologies, DOE has no such capability for ARPA-E to leverage. While DOE has an energy loan guarantee program, it is not structured to finance new technologies without a performance track record.[52]

This suggests that there is an earlier stage problem, too, that ARPA-E faces for its energy technologies. Energy technologies are unlikely to be adopted by energy industries, as noted above, until their cost, reliability, performance and efficiency is well-proven. For example, while 40% of CO2 emissions come from the building sector, this sector is highly characterized by numerous locally-based firms; it is decentralized, undercapitalized, undertakes little R&D and is risk-averse. It simply will not adopt technology advances until they are well-proven. Similar problems abound in other energy sectors. A testbed capability has been the remedy for this problem, historically. Such testbeds, then, are increasingly important in energy technology implementation to create the prerequisite demonstrations that will allow commercialization to proceed. This is likely not only going to be ARPA-E's challenge. As entry gets more difficult for DARPA's technologies, a similar testbed capability could become significant. While DOD has long developed testbed capacity, they are not readily connected to DARPA's breakthrough technology model.

DOD has been working on exactly this problem of a connected handoff from R&D to testbed in two interesting energy-related programs. The Strategic Environmental Research and Development Program (SERDP), formed in 1990, is a DOD R&D program housed within the Office of the Deputy Undersecretary of Defense for Installations and Environment in the Office of the Secretary of Defense. DOD, EPA and DOE share an oversight role over the program. It is coupled to the Environmental Security Technology Certification Program (ESTCP), formed in 1995, which tests environmental and energy technologies emerging from SERDP and elsewhere, which are near deployment but require demonstration and validation through a testbed. The programs' online mission statement states that SERDP and ESTCP are DOD's environmental research programs,

> …harnessing the latest science and technology to improve DoD's environmental performance, reduce costs, and enhance and sustain mission capabilities. The Programs respond to environmental technology requirements that are common to all of the military Services, complementing the Services' research programs. SERDP and ESTCP promote partnerships and collaboration among academia, industry, the

[52] "DOE has had a significant loan guarantee program since 2005 but did not issue loans until 2009. It has a mandate to 'facilitate the introduction of new or significantly improved energy technologies with a high probability of commercial success in the marketplace.' Although the program is aimed at helping move technologies past the initial commercialization barrier, the mandate's language builds in potential contradictions. It is limited to deployment-ready projects, so it excludes demonstrations, and the 'high probability of commercial success' clause, perhaps due to the legacy of failed 1980s synfuels projects, significantly limits the risks that the program can take with innovative technologies." (Bonvillian 2011b).

military Services, and other Federal agencies. They are independent programs managed from a joint office to coordinate the full spectrum of efforts, from basic and applied research to field demonstration and validation. (Department of Defense 2011a (SERDP and ESTCP)).

In turn, once through the demonstration process, ESTCP works with DOD's installations programs to enable initial deployment of successfully tested technologies. The director and architect of SERDP and ESTCP, Dr. Jeff Marqusee, has stated regarding ESTCP that, "We can serve as a test bed to get these technologies over the valley of death, and then we can be an early market. The calculation is pretty straightforward. If we test ten technologies, and one is highly successful, we can deploy that in a hundred places [through DOD] and make it profitable."[53] These entities amount to an interesting new model for the energy/environment field from DOD, explicitly and closely linking R&D, testbeds and initial deployment.

A review of pending energy projects by the two connected programs indicates work by United Technologies on methodology and tools for building systems on DOD installations with a 50% efficiency improvement, an air source cold climate heat pump with Purdue researchers, and demonstration of high gain solar for distributed energy needs at DOD facilities with Skyline Solar.[54] ESTCP demonstration work in microgrids, storage, and building efficiency controls is ongoing. Funding for a new energy testbed capability at DOD installations received $30m in funding in DOD's FY12 budget (Robyn 2011). A significant expansion of linked R&D and testbeds as well as a connection to initial market capability may be one answer to the implementation challenge ARPA-E faces.

In the long list of challenges ARPA-E faces, the problem of technology implementation is perhaps the most profound. This is because, to reemphasize the point, of the difficulty new energy technologies face not only with the problem of the "valley of death" in moving from research to late stage development, but the problem endemic to CELS of "market launch"—implementing technology at scale. ARPA-E has worked imaginatively to structure new elements into its model to address this problem. The approach of SERDP and ESTCP provides an interesting new model in the energy area for ARPA-E to consider as it focuses on technology implementation. Collaboration with these programs, which ARPA-E is actively working on, may provide a crucial new toolset.

ARPA-E is not alone in facing this implementation problem; the applied agencies at DOE, led by EERE, face a similar problem and the SERDP/ESTCP combined model of R&D-testbed-deployment offers an interesting new approach. DARPA, too, despite remarkable past successes, is not immune, as discussed above, from the implementation problem. With the budgetary constraints facing DOD for new systems development and the weakening posture of risk investments and venture capital in the commercial US markets with the drive toward outsourcing and offshoring, implementation of DARPA programs appears to be a growing problem. DARPA also might learn lessons and make further uses of the SERDP/ESTCP approach. In addition, DARPA could consider tools such as Mantech and the Defense Production Act as the source of demonstration and initial deployment particularly for its manufacturing initiatives.

In summary, implementation presents a major challenge for both agencies. DARPA needs to consider its existing portfolio of implementation support, including ties to SERDP/ESTCP, building its manufacturing research efforts, and linking with Mantech and

[53] Comment cited in Hourihan and Stepp (2001, 17). See, also, Marqusee (2011).

[54] See program list in Department of Defense (2011b) (SERDP and ESTCP Energy and Water Projects).

the Defense Production Act authority. ARPA-E has worked imaginatively on its implementation capabilities, but the complexity of its task requires it to consider additional mechanisms, including further collaboration with DOD, connecting to the SERDP/ESTCP model, and designing within its research projects efforts to drive down costs. These could be coupled to expansion of the interesting new features it is working on to spur development, as well as adapting DARPA concepts of multigenerational technology thrust, connecting to larger innovation elements, strategic connections between technologies, further building of its support community, and expanding its first adopter/initial market role.

5 Conclusion: Brief summary of key points

ARPA-E offers a very interesting new innovation institution to meet the profound energy technology challenge discussed in the introduction. Because it is explicitly modeled on DARPA, this paper has reviewed the noted DARPA approach in detail. Both agencies offer models for innovation organization that could more broadly apply to other R&D agencies. Briefly citing well-known features of DARPA, the article explores in detail a number of important features that have not been well discussed in the policy literature on DARPA to date. These include DARPA's ability to undertake multigenerational technology thrusts, the technology synergies it has been able to create through complementary strategic technologies, its ability to build an advocate community, and connections it has built to larger innovation elements downstream from DARPA. In addition, it has been willing to take on incumbent technologies both within DOD and in the private sector, used ties to DOD leadership to press its advances, and doesn't necessarily launch to a free market by playing roles as first adopter and in initial market creation.

The paper then reviews the new ARPA-E model in detail. It first comments on just how ARPA-E has adopted the key elements of the DARPA approach. It then discusses new features ARPA-E has been moving toward in a series of areas, largely driven by its need to confront the unique and difficult demands of the complex established energy sector where it operates. In the area of sharpening the research visioning, selection and support process, it is focused on: the "white space" where tech opportunities are not being advanced in other parts of the innovation system; on an interesting two-stage feedback system for selecting technologies; encouraging its PMs to "get religion" about their technologies to become vision enablers; using a new fellows program to get access intergenerational contact and additional ideas; a portfolio approach that mixes ranges of technology risk; and encouraging a very hands-on relationship between PMs and researchers.

ARPA-E has also been making progress in building a community of support, important to its political survival. This includes building internal connections with other DOE agencies, holding a highly successful community-building energy technology summit, and fostering a broad support community. On the battlefront of technology implementation, ARPA-E has: encouraged consideration of the implementation process in the selection of technology projects; worked on "in-reach" within DOE to move its technologies into the applied side; created ties to DOD for possible test bed and initial market capability; formed an internal commercialization team to work with PMs to move their technologies into implementation; connected technologies to the industry "stage gate" process; encouraged industry consortia around its projects, and is planning to use prize authority.

In addition, the further DARPA features enumerated above provide potentially useful guideposts to ARPA-E as it continues to support innovation in the energy sector.

These include DARPA's multigenerational thrust, strategic relations between technologies, an advocate community, connections to larger innovation elements, coping with incumbents, seeking initial markets for its technologies, and further ties to leadership.

Finally, the paper closes with a discussion of the profound technology implementation problems on the "back end" of the innovation system—including demonstration, test beds, initial markets. The authors believe both agencies must explicitly, imaginatively and actively address the implementation issue. When new, radical, transformational technologies are seen as needed, either for national security, energy security, or economic security, there are sufficient impediments within the existing governmental organizations and within the existing markets that creative partnering between the government and private sector is required to address the downstream risks, while recognizing that the best means to mediate risk is through innovation, not stasis. We believe that the agencies need to expand their innovation efforts in technology implementation by developing further approaches for fostering downstream partnerships between the government and private industry.

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